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EVALUATION OF THE POTENTIAL FOR REDUCED LONGITUDINAL SPACING ON FINAL APPROACH

William J. Swedish

The MITRE Corporation
Metrek Division
McLean, Virginia 22102

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16. Abstract

Reducing the separations between aircraft can improve airport capacity and decrease delays. This report addresses the feasibility of reduced IFR separation standards on final approach, and identifies the characteristics of the ATC system which affect or are affected by the separation standards.

This study has been limited to conditions during which wake turbulence is not a factor. Given this assumption, separation reduction will be most limited by the need to avoid simultaneous runway occupancy by successive arrivals. As the interval between landings decreases, so must the time spent on the runway, if dual runway occupancy is to be avoided. For acceptable performance, the average runway occupancy time must be no more than 50 seconds for a 2.5 nmi minimum separation standard or 37 seconds for a 2.0 nmi standard, with the current ATC system. Various technical improvements now under development may make it possible to operate a 2.0 nmi minimum with average runway occupancies as great as 45-50 seconds. Adequate communications and surveillance for the controller, and enforcement of current ATC procedures are also required for operations with reduced separations.

An alternative solution to the runway occupancy problem is to use a pair of close-spaced, dependent (dual-lane) runways and alternate arrivals between them.

Reduced separation on approach to a single runway cannot be realized until the wake vortex problem is resolved. Although there do not appear to be any other technical or operational barriers to reduced separation standards, additional research is required before reduced standards can be implemented.

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In addition, thanks are due to Marty Ditmore of MITRE for his work in studying operations at National Airport; to Carlos Saavedra for his work at National Airport, especially his analysis of communications channel usage; and to Steve Koenig, for sharing his analysis and insights on runway occupancy times.

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EXECUTIVE SUMMARY

Conclusions

- Reductions in IFR approach spacing can be achieved safely at high-density hub airports without higher go-around rates or increased controller workload by improving runway occupancy times and/or the over-threshold delivery accuracy of the terminal air traffic control system.

- Average runway occupancy times today vary widely by airport, runway and carrier in the range from 41 to 63 seconds. There exists considerable latitude to reduce average occupancy times below 50 seconds for most current runways when proper motivation for such reductions is established.

- An IFR minimum of 2.5 nmi is achievable, with average runway occupancy times (50 sec) routinely obtained today on many major air carrier runways, if wake vortex restrictions can be safely reduced. The remaining questions to be resolved are operational rather than research in nature, and relate primarily to establishing uniform procedures for and achieving operational acceptance of the reduction to 2.5 nmi.

- A 2 nmi IFR minimum cannot be achieved and sustained with the current manual ATC capability. The runway occupancy times (37-39 sec) that would be required with manual over-threshold delivery accuracies are not ordinarily achieved with today's aircraft on present runways.

- A 2 nmi IFR minimum for air carrier aircraft at major airports can be achieved with the improved ATC capabilities of a terminal flow management system and runway occupancy times in the range of 45-50 seconds, assuming that the wake vortex problem can be dealt with. An equivalent capacity improvement might be possible by use of a combination of cockpit traffic displays for airborne and runway self-spacing, and 4D area navigation to tighten up over-threshold delivery accuracy. However, the technical risk of this approach is much higher since it requires development and integration of complex cockpit and flight control systems that are capable of rapid and precise adaptation to varying airport and runway traffic conditions, data on which would need to be transmitted from the ground system. A more likely role for traffic displays on approach is in the passive monitoring of spacings from other airborne (and possibly on-runway) aircraft.

Major problems needing resolution in order to meet a goal of 2 nmi include:

-- Development of vortex systems designs and verification of the safety and performance of such systems at spacings below 3 nmi.

-- Establishment of minimum pilot/local controller communications requirements to ensure responsiveness in go-around situations.

-- Determination of the role and need for pilot situation monitoring and cockpit traffic displays in the acceptance of a 2 nmi minimum standard.

- The specific requirements for reduced IFR separations will require airport-by-airport implementation of the reductions. Universal implementation is neither feasible nor necessary.

- Closely spaced parallel runways (700-3000 ft) operated with alternating ILS approaches to each runway provide an additional potential source for improvements in runway occupancy and ATC. Several new questions of vortex and operational safety (in particular, lateral transport of vortices, proper runway identification, and controller parallel approach monitoring requirements) must be resolved, however, to make this approach useful.

Recommendations

1. The vortex data base accumulated to support the development of the Vortex Advisory System (VAS) should be reanalyzed to establish the feasibility of the use of VAS to support spacings below 3 nmi. Three areas should be evaluated for applicability and effectiveness at 2.5 and 2 nmi:

   a. Use of the present VAS design concept with a revised ellipse for reduced spacings.

   b. Use of a VAS design that is augmented by additional meteorological data (e.g., turbulence measures) to improve effectiveness at reduced spacings.

   c. Modifications of VAS (or of the augmented VAS) to support development of dependent close spaced parallel approaches:

-- with coplanar approach paths

-- with staggered thresholds and/or different glide slope angles.

This analysis should also identify aircraft pairs without vortex hazards, should evaluate the impact on ATC-initiated go-around rates of VAS changes (i.e., green to red), and should include as an integral component extensions of the VAS safety analysis to cover these reduced spacing options. In addition, procedures for transitioning from en route separations to the lower VAS spacings should be investigated.

2. It is recommended that the FAA expedite the development of the definition of a ground-based advanced wake vortex system and the establishment of a baseline design, operational analysis, and cost projection. At the present time, it is impossible to establish design performance or a program plan for such a system since it has not yet been adequately defined.

3. A thorough exploration, in the joint NASA/FAA program, of the alternative of vortex alleviation by modification of the generation mechanism at the source, is recommended. This program should not only consider a return to the 3 nmi spacing, but also address the potential for further reductions in spacing by these means. The operational requirements of alleviation should also be addressed. Such a program including analysis, wind tunnel and flight testing of the full spectrum of vortex alleviation approaches to spacing reduction could be developed by FAA and NASA.

4. The analysis of the potential for reduced spacing depends, in part, on several numerical assumptions that will require confirmation by collection of data in the field.

   It is recommended that the FAA develop a specification for the collection of the needed data by FAA or contractors. The data specification and subsequent collection activity should address the following elements:

   a. Relationship of available data on VMC runway occupancy times to that achievable in IMC with both wet and dry runways.

   b. Local control channel communications usage by pilot and controller, under a variety of airport procedures.

   c. Rates of controller interventions for spacing purposes and of controller initiated go-arounds, particularly in IMC.

The preparation of draft specifications for the collection of these data is being undertaken as a follow-on to the present studies. The data should then be related to the results of the present analysis, and a sensitivity analysis should be prepared.

5. The distribution of interarrival spacings is a critical input to the calculation of intervention and event rates, and to the subsequent evaluation of the potential for 2 nmi spacings. The current FAA Metering and Spacing program should include the measurement of before/after interarrival time distributions in order to demonstrate the actual improvement (reduction in interarrival time dispersion) that may be expected from an implemented Metering and Spacing system.

6. The human performance aspects of the go-around process, such as pilot landing expectations and response to go-around commands, as well as pilot/controller workload and controller judgments of aircraft spacings and requirements for intervention, need to be studied. A first step would be for FAA/NASA to define a real time simulation and flight test program (NASA Langley) directed toward the problems of reduced final approach spacing, to be performed in conjunction with the current FAA human factors programs. The outputs of such a program could lead to improved, standardized local control procedures on final approach, and could identify any requirements for specialized communications channels or cockpit displays.

   It would be desirable to incorporate the possible requirements for cockpit displays for 2 nmi spacing (to single runways) into studies and analyses of cockpit display systems. A first step would be to prepare a preliminary statement of these requirements and a plan for research. The initial requirements and plan can be modified and updated by the findings of the human factors simulations and flight tests, described above. However, it is essential that the basic concepts of cockpit displays to support reduced approach spacings be introduced into the cockpit display program as early as possible. This initial plan should include evaluation of the use of cockpit displays for:

   -- Pilot verification of need for go-around

   -- Pilot initiation of go-around

   -- Precise traffic spacing (with RNAV) in lieu of metering and spacing by the controller or a semi-automated system.

   The effect of these options on controller performance should also be tested.

7. A review should be conducted of current FAA programs to reduce runway occupancy times and to improve runway surface and braking conditions, as well as exit marking and lighting. The potential impact of these improvements on the runway occupancy times of the specific runways at major airports that would be candidates for reduced separation operations should be estimated.

8. Closely spaced parallel (i.e., dual lane) runways, operated with alternating ILS approaches, provide an attractive method for supporting reduced IFR spacing without the constraints imposed on single runways by long runway occupancy times and manual traffic spacing. The details of such procedures should be further evaluated to determine the true potential for spacing reductions on dependent parallel runways. Issues that need to be addressed include:

    -- Potential wake vortex interrelationships between the approaches to the two runways.

    -- Lateral, longitudinal and vertical separation requirements and tradeoffs.

    -- Requirements for interarrival time accuracies, whether by manual or automated spacing, as well as associated procedural requirements.

    -- Requirements for ILS/MLS navigational accuracy.

    -- Potential advantages of staggered thresholds, varied glide slope angles, and uses of a MLS.

    -- Requirements for local controller surveillance of the runway and final approach environment.

    -- Techniques for management of aircraft on runways and taxiways, including the mixing of departures.

    -- Techniques and requirements for safety assurance in the identification of the proper ILS and runway, and control of runway crossings.

    -- Potential for improvement in runway capacity, as a function of the specific airport's layout and other constraints.

The initial phases of this activity are being undertaken as a follow-on to the present study, as well as in response to issues raised at several Airport Improvement Task Forces.

9. Reduced IFR separation requirements, particularly those requiring continuous controller surveillance of the taxiways, runway and last mile of approach, should be incorporated into plans for Airport Surface Traffic Control systems and other related surveillance projects.

10. Representatives of airline pilot organizations and air carriers that operate large aircraft should be asked to develop a plan to improve pilot runway occupancy performance. This plan should consider two future regimes:

    -- The use of present equipment with revised procedures.

    -- The use of improved equipment (i.e., automatic braking, ground speed indication through INS, new exit lighting and marking, or other means).

11. In order to provide the basis for development of a complete safety analysis of reduced spacing, and of public confidence in and acceptance of the results, this analysis should be reviewed with the FAA operating services and pilot and operator user groups. Such review should include discussion of the methods, assumptions and conclusions of this study.

12. All participants in the above review should then identify the elements to be required of a complete safety analysis of reduced spacing, and the analytical and/or live test techniques that will be employed prior to implementation of reduced separations. It is recommended that the FAA then prepare a plan for accomplishing the safety analysis, in parallel with the other recommended activities, in order that all factors of concern will have been identified and evaluated prior to any move towards implementation of separations below 3 nmi.

OVERVIEW OF ANALYSIS

BACKGROUND

Statement of the Problem

The hazard presented to following aircraft by wake vortices has caused the longitudinal separations between aircraft to be increased, from a minimum IFR separation standard of 3 nmi (nautical miles) to as much as 6 nmi in the terminal area. Several FAA and NASA research projects are aimed at the avoidance or alleviation of wake vortices; increased airport capacity and reduced aircraft delay would result if the 3 nmi minimum separation could be restored.

Further improvements in capacity and delay would occur if minimum separations were reduced below 3 nmi. The FAA's Office of Systems Engineering Management has tasked MITRE to study the feasibility of such reductions. Wake vortices pose a hazard that must be alleviated before separations can be reduced to any lower values and are the subject of ongoing research. The purpose of the MITRE study was to determine if other problems exist at reduced separations and if so, whether any are so serious as to preclude the reductions.

Included in the investigation were the factors affecting current separation standards, the additional factors that would affect reduced standards, and the need for user acceptance of reduced standards. It should be noted that where actual separations are governed by external factors, such as icy runways or interleaved departures, such spacings will not be affected by reducing the minimum standards.

User Group Meetings

One of the first stages of the investigation involved a discussion of reduced separations with representatives of the Air Transport Association, Aircraft Owners and Pilots Association, Air Line Pilots Association, National Business Aircraft Association, and the U. S. Air Force. These meetings were held to learn the particular concerns of the user groups.

The representatives we spoke to were primarily concerned with the unknown effects of wake vortices at the lower separations, although this was a factor that was excluded from direct consideration in this study. Their next major concern was the rate of go-arounds that might be required to avoid simultaneous runway

occupancy. Reduced longitudinal separations would reduce the average length of time during which the runway was unoccupied between arrivals, and would, therefore, increase the probability of either having two aircraft on the runway simultaneously or requiring a go-around to avoid such a condition. Two suggested approaches for resolving this problem were to reduce runway occupancy times or to use a close-spaced parallel runway for alternate arrivals.

Other user concerns were expressed, including ILS signal interference, beacon system garbling, and the potential for conflict between consecutive go-arounds, but these do not appear to present serious impediments to reduced separations.

ANALYSIS OF REDUCED SEPARATIONS

Go-Arounds to Avoid Simultaneous Runway Occupancy

A go-around can lead to significant delay and fuel cost for the aircraft involved and additional workload for the controller, as well as potential safety hazards from the additional nonstandard maneuvers required. Consequently, a go-around is only used as a last resort to avoid simultaneous runway occupancy. The controller will normally use buffers (i.e., additional spacing above the minimum standards) in the control process to reduce the frequency of occurrence of such tight situations to an acceptable level.

We have assumed that the controller in the present manual system allows a 5% probability buffer between average runway occupancy time and the minimum separation standard. For the standard "reference runway" which was used in this analysis, this 5% buffer equals 14s (seconds). Since two aircraft separated by the minimum 3 nmi spacing will cross the threshold 77s apart (assuming a 140 kt approach speed), this 14s buffer means that the average runway occupancy can be no greater than 63s (see Figure 1). At larger average occupancy times, more than 5% of the arrivals would be on the runway longer than 77s, leading to an unacceptable number of go-arounds unless the controller increased the minimum separation above the 3 nmi standard.

Figure 1 also shows that a buffer is applied to the interarrival time between aircraft, to increase the average separation above the minimum standard. The combination of these two buffers reduces the probability that a go-around would be required to prevent simultaneous runway occupancy, that is, that two aircraft would otherwise be on the runway at the same time. The

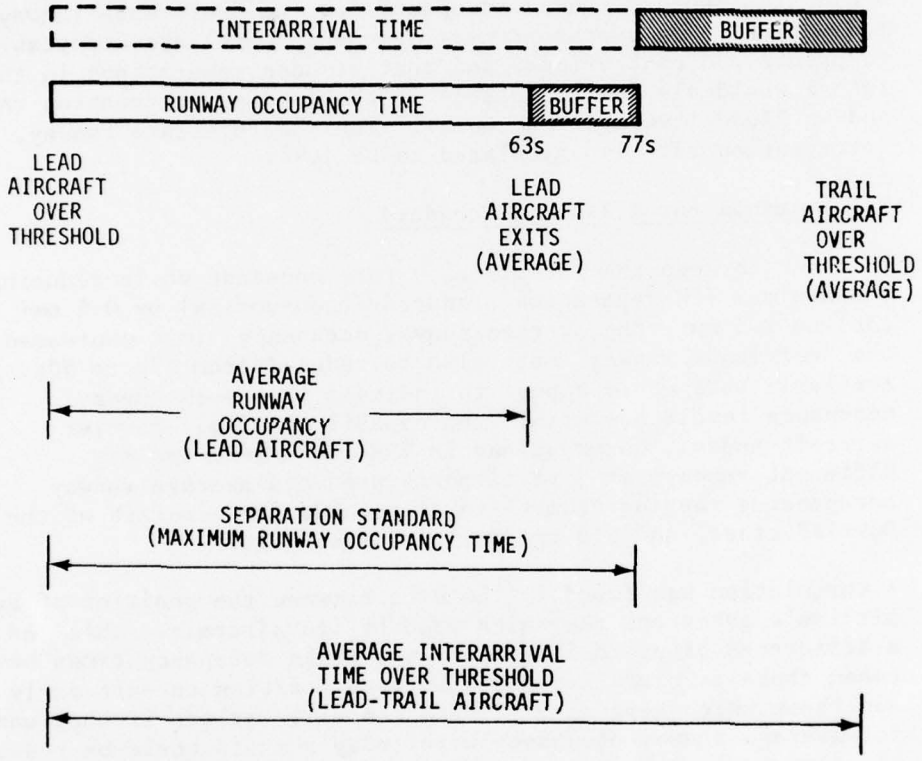

FIGURE 1
THE REFERENCE RUNWAY

controller may also intervene directly in the spacing process -- by vector spacing, reduced speeds, or an expedited exit request -- to avoid a go-around. Since we cannot predict the form that this controller intervention might take, we cannot predict how often it would be unsuccessful and a go-around would be required. However, it is possible to calculate the rate of controller intervention, based upon normal distributions of runway occupancy time and interarrival time, and assume that the number of go-arounds remains in constant proportion to the number of interventions.

Consequently, the central assumptions of this analysis are that the controller intervention rate and workload levels needed to avoid simultaneous runway occupancy for the "reference runway" today (i.e., 63s average runway occupancy time) are acceptable to pilots and controllers, and that reduced separations in the future would also be acceptable if the future intervention rate and workload levels are no worse. For the reference runway, the intervention rate is calculated to be 1.4%.

Requirements for a 2.5 nmi Standard

In order to keep the intervention rate constant while reducing the minimum IFR separation standards (non-vortex) by 0.5 nmi (or 13s) to 2.5 nmi, the average runway occupancy limit expressed by the "reference runway" must also be reduced from 63s to 50s. Available data would appear to indicate that such runway occupancy levels are within the capability of air-carrier aircraft today. Observations in VFR conditions for six different runways at five airports produced average runway occupancies ranging from 41 to 51 seconds for aircraft of the DC9-727 class, and 51s to 58s for larger jets.

A correlation was found in the data between the position of an airline's gates and the exits used by its aircraft. This led to a difference of up to 8 seconds in average occupancy times between those carriers motivated by gate position to exit early and those which were not. Pilots can exit earlier if they want to; average runway occupancy with today's exits could be reduced if pilot motivation to quickly clear the runway could be improved. Selected additional exits could also be constructed.

Other requirements for a 2.5 nmi separation standard include adequate controller surveillance of the approach path, runway, and taxiways, and the conscientious application of existing ATC procedures. No special problems were found to be caused by the increased traffic densities of the reduced separations.

Requirements for a 2 nmi Standard

If separation standards were further reduced to 2 nmi, the rate of controller interventions (and the implicit go-around rate) would increase unless the average occupancy time were 37 seconds or less. It is doubtful that with current equipment such low runway occupancy levels could be achieved and maintained consistently, especially in IFR conditions. Fortunately, there are approaches to the question of simultaneous runway occupancy other than simply reducing average occupancy times.

The controller intervention rate is a function of the standard deviations, as well as the averages, of runway occupancy time and interarrival time (represented as σ_R and σ_I, respectively). A one-third (approximate) reduction in σ_R would raise the required average occupancy time to 39s. An automated Metering and Spacing system, which would reduce σ_I from 18s presently to 11s, would permit operations at the 2.0 nmi standard with no change in the controller intervention rate if the average runway occupancy time is no greater than 47s, or 50s if σ_R is also reduced. This benefit is achieved by more accurate control of the interarrival spacing and the use of a 1% rather than a 5% buffer on interarrival time. Such occupancy times of 47 to 50s are not greatly different from those observed at major airports today during VFR conditions.

When σ_I is reduced, the controller intervention rate may no longer be an adequate measure of controller workload. Reducing σ_I tightens the distribution of interarrival times, which increases the number of aircraft which come close to requiring intervention, and therefore the number of active decisions required of the controller. For example, we have defined the case where the lead aircraft is still on the runway when the trail aircraft is one-half mile from the threshold. The controller typically prefers to issue a go-around command, if required, no later than this half-mile point; therefore, this situation would require the controller to project the dynamic situation and decide whether or not the aircraft on the runway will be off in time. Clearly, this represents additional controller workload, which we would prefer to keep at current levels.

The probability of occurrence of the situation described above will be called the "event rate." For the 3 nmi reference runway, the required intervention rate is 1.4%, but the event rate is 6.1%. Keeping the required intervention rate constant at

1.4% for 2 nmi with automated Metering and Spacing, as described above, would lead to an increased event rate of 11-12%. To keep the event rate constant so as not to increase the controller's decision-making workload, would require a mean runway occupancy time of 43s, or 45s with a reduced σ_R. These mean occupancy times would also have the beneficial effect of reducing the required intervention rate to about 0.6%. These results are shown in Table 1.

The average runway occupancy times required to keep the event rate constant are therefore not drastically different from those resulting from the constant intervention rate requirement. It may thus be concluded that a 2 nmi separation standard can be implemented with feasible levels of average runway occupancy, and an automated Metering and Spacing system.

Other Possible Requirements for Separation Reduction

Reduced separations will lead to increased numbers of aircraft in the terminal area and additional loading on the communication channels. The controllers we spoke to were confident that they could handle the additional communications workload for routine operations. A concern has arisen, however, that the extra communications will interfere with the local controller's ability to deliver an emergency command such as an order to execute a go-around.

When the channel is not in use, or if the controller is transmitting, there would be no delay in gaining access to the channel and delivering the emergency command. If the pilot is transmitting, the controller must wait for the end of the message; otherwise the interference between the two transmissions would render them both unintelligible. Fortunately, most pilot transmissions are short; the expected waiting time today for the local controller to deliver a command is very low.

Prompt delivery of the go-around command is one of several areas which may be more important for user acceptance of reduced separations than for operational or technical reasons. Although no problem is expected, user perception that a problem exists may require that action be taken. For example, a separate radio frequency could be reserved for time-critical commands; the emergency frequency of 121.5 MHz or the ILS localizer frequency are possibilities. DABS data link could be used for the commands or, conversely, could be used for routine messages,

TABLE 1

INTERVENTION AND EVENT RATES

	INTERVENTION RATE HELD CONSTANT	EVENT RATE HELD CONSTANT
INTERVENTION (EVENT) RATES ON REFERENCE RUNWAY TODAY	1.4% (6.1%)	1.4% (6.1%)
INTERVENTION (EVENT) RATES WITH 2 NMI SEPARATION, REDUCED RUNWAY OCCUPANCY SIGMA AND METERING & SPACING	1.4% (12%)	0.6% (6.1%)
REQUIREMENT FOR AVERAGE RUNWAY OCCUPANCY TIME	50s	45s

reserving voice radio for the critical transmissions. Or non-radio means such as flashing threshold lights might be used to signal a go-around.

Alternatively, information adequate for making the go-around decision could be provided directly to the pilot, perhaps as part of an instrument panel mounted CDTI (Cockpit Display of Traffic Information) or incorporated in the HUD (Head Up Display -- primarily used for aircraft guidance and control information). The information presented on such displays could also be presented to the controller who may be better able to determine the need for a go-around. However, the displays would probably enhance pilot confidence in reduced separations by providing the pilot with additional information on the locations of other aircraft. The pilot would therefore have either positive assurance that no conflict was developing, or else an early and independent warning if one did.

A reduction in σ_I due to improved navigation has also been claimed for a version of CDTI. Further research on cockpit displays will be required to determine true capabilities and impact on actual operations, especially under conditions when not all aircraft are so equipped.

Dependent Parallel Runways

The probability of simultaneous runway occupancy could be greatly reduced, even with reduced airborne separation standards, if separate runways were used by successive aircraft. One means to accomplish this is to form a single stream of arrivals at reduced spacings and then sidestep every other aircraft to a second runway. However, this technique is limited by the maneuverability of large aircraft and the relatively high weather minima associated with this type of approach.

Another procedure is to operate two parallel streams of staggered arrivals to a pair of close-spaced dependent runways. A preliminary analysis of such operations revealed no significant operational problems even at reduced separations. The time between successive arrivals to the same runway is much greater than the typical runway occupancy time. Consequently, the effect of an unusually short interarrival time or unusually long runway time would not be a go-around, as it would be for a single runway, but only a lost departure gap between arrivals.

The use of staggered arrivals in IFR conditions implies that ILS guidance is available to both runways. Operational experience at San Francisco International, where the runways are 750 feet apart and ILSs on both runways are always operational, is that no interference between the ILSs is likely. Neither is radar beacon garbling, another potential problem for aircraft spaced below 3 nmi, observed as a significant problem or operational limitation when reduced spacings are employed for VFR traffic at San Francisco.

Additional areas for further research include the effects of wake vortices, impact on controller workload, methods of maintaining airborne separations, and requirements for special surveillance equipment or procedures. However, the concept shows great potential benefit.

Conclusions

Reductions in IFR approach spacings can be achieved safely without higher go-around rates or increased controller workload by improving runway occupancy times and/or the over-threshold delivery accuracy of the terminal air traffic control system.

Average runway occupancy times today vary widely by airport, runway and carrier in the range from 41 to 63 seconds. There exists considerable latitude to reduce average occupancy times below 50 seconds for most current runways when proper motivation for such reductions is established.

A 2.5 nmi minimum IFR separation is achievable with average runway occupancy times (50 sec) routinely obtained today on many major air carrier runways, if wake vortex restrictions can be safely reduced. The remaining questions to be resolved are operational rather than research in nature, and relate primarily to establishing uniform procedures for and achieving operational acceptance of the reduction to 2.5 nmi.

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Major problems needing resolution in order to meet a goal of 2 nmi include:

-- Development of vortex systems designs and verification of the safety and performance of such systems at spacings below 3 nmi.

-- Establishment of minimum pilot/local controller communications requirements to ensure responsiveness in go-around situations.

-- Determination of the role and need for pilot situation monitoring and cockpit traffic displays in the acceptance of a 2 nmi minimum standard.

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1. INTRODUCTION

1.1 Background

1.1.1 The Need for Reduced Separations

The domestic air carriers are currently experiencing a phenomenal growth in passenger traffic. The actual number of flights has increased much more modestly, however. Although there are many practical and economic reasons for the airlines' reluctance to schedule more flights, one factor is surely the realization that additional flights would only worsen the delays already being experienced at the major airports. For the first six months of 1978, the number of aircraft delayed more than 30 minutes increased by as much as 300% (at Los Angeles) over the same period of 1977 (Reference 1).

In the past, a typical approach to reduction of aircraft delays has been to increase airport capacity by building additional runways. This solution is no longer possible at the major airports where it is most needed, due to noise and environmental constraints and the lack of available land. Instead, it is necessary today to make more efficient use of the facilities which are currently available.

This situation was recognized in 1969 by the Air Traffic Control Advisory Committee (ATCAC) of the U.S. Department of Transportation. ATCAC was formed after air traffic delays rose to unprecedented levels at U.S. airports in the summer of 1968. One of ATCAC's proposals to improve airport capacity and reduce delays was to reduce the longitudinal spacing between aircraft from a minimum of 3 nmi in the terminal area in IFR to 2 nmi (Reference 2).

Shortly thereafter, however, the FAA acted to increase separations, not decrease them. The widebodied aircraft, which had been introduced just prior to that time, produced strong trailing wake vortices which could (and did) cause accidents for aircraft following too closely behind. As a consequence, minimum IFR separations were increased from 3.0 nmi to as much as 5.0 nmi (later 6.0 nmi) for aircraft following a "heavy" aircraft, i.e., an airplane with a certificated maximum gross takeoff weight of 300,000 pounds or more.

The effect on aircraft delays of this procedural change was tempered by a downturn in airline traffic due to economic

conditions, by the greater passenger capacity of the wide-bodies themselves, and by other changes in airport and ATC operations. Nevertheless, the reduction in capacity and consequent increase in delays caused by the wake vortex rules has always been recognized, and much effort has gone towards a return to the three mile rule.

Two separate principal directions have been followed in this research. The FAA has been investigating methods, such as the Vortex Advisory System (VAS) currently being tested at O'Hare, for detecting atmospheric conditions which alleviate the vortex hazard by dissipating the vortices rapidly or by moving them out of the approach corridor. NASA is investigating dissipation of the vortices at the source by aerodynamic means, such as selective spoiler deployment in flight. Other approaches, such as class sequencing, are also being investigated. Class sequencing would minimize the effects of vortex-induced separations by segregating traffic by size to the extent possible, and would increase the benefits of reducing separations between aircraft of the same class. The prospects are good that one of these approaches will allow a relaxation of the vortex rules in at least some situations.

1.1.2 MITRE Research on Reduced Separations

Once it is possible to deal with the wake vortex hazard, further separation reductions such as recommended by ATCAC will be worth considering. Not only will airline traffic continue to grow in the years to come, putting more pressure on existing airport capacity, but the cost of delay will go up as fuel becomes even more expensive. Consequently, the FAA's Office of Systems Engineering Management (OSEM) has tasked MITRE to study the question of separation standard reductions, and specifically to determine the critical factors involved in implementing such reductions.

In MTR-7333, "An Analysis of a 2.5 nmi Final Approach Separation Standard" (Reference 3), the technical feasibility of an immediate reduction in the separation standard was studied. The report concluded that a 2.5 nmi standard would have a significant beneficial effect on capacity and would be technically feasible if the wake vortex problem could be dealt with.

The current report extends the analysis presented in MTR-7333 by considering operational factors as well as technical feasibility. It is also not limited to either a single reduced standard or to the current ATC system. This report will attempt

to identify areas where further research is required, new equipment is needed or new procedures must be developed before reduced separations can be implemented.

1.2 Objectives and Limitations

1.2.1 Purpose and Objectives of this Analysis

The goal of MITRE's efforts for OSEM in this area has been to help the FAA assess the feasibility and desirability of reduced separation standards and to assist the FAA to prepare for eventual formal implementation of reduced separations. The purpose of the current study was to establish a background for future implementation efforts, by resolving some of the basic questions concerning separation reduction. These include:

- What are the major factors affecting the current 3.0 nmi separation standard?
- How do controllers interpret this requirement, and how does their interpretation of other requirements affect the separation standard?
- What additional factors would be significant at reduced separations which are of only secondary importance today?
- How can the reduced separation standards be analyzed for operational feasibility?
- How would the various user groups react to reduced separation standards?
- What actions must be taken to improve user acceptance of reduced separations?
- Should reduced separations be implemented for all airports, for a given class of airport, or on an individual airport basis?

The answers to these questions are expected to help indicate the directions which should be taken by the FAA's research efforts in order to facilitate separation reductions and to be useful in the implementation process itself.

1.2.2 Restrictions and Limitations

This study will attempt to consider all the relevant factors which affect minimum IFR separations in the terminal area, with the exception of wake vortices. This is not to say that wake vortices do not have a significant influence on the separation standards; on the contrary, they are the single reason why current separations are as large as they are.

However, the emphasis on the wake vortex problem has overshadowed the other factors affecting separation standards. It seems likely that a method will be found to deal with wake vortices, either by alleviating them at the source or by recognizing the conditions which cause rapid dissipation and weakening of the vortices. Rather than be unprepared when a successful vortex program goes into effect, it was decided to concentrate on the non-vortex factors which affect separations.

The decision was also made to limit this study to IFR separations in the terminal areas of high-density hub airports. If only terminal-area or final approach separations, and not en route separations, can be reduced below the values required by the wake-vortex hazard (as might perhaps occur if a ground-based system like VAS or WVAS were used), then transitioning from the larger en route spacing to the smaller terminal separations might be difficult. A recent MITRE report (Reference 4) analyzed this problem, and determined that reliance on speed differentials between consecutive aircraft to close up the spacings (the "accordion effect") would be only partially successful. Two other schemes, involving the vertical or horizontal merging of two separate arrival streams, were found to allow dependable transitions to final spacings as low as 2.0 nmi. Reference 4 discusses the pros and cons of the three different transition procedures and the associated requirements on the WVAS system. We shall assume in this report that the need to transition from en route separation to reduced terminal separation does not prevent the full attainment of the lower spacings, either because procedures such as vertical or horizontal merging are in effect, or because en route separations have also been reduced.

IFR separations and not VFR separations will be studied because, although most operations occur in VFR conditions, most delays occur during IFR conditions, emphasizing the need to improve IFR capacity. Also, IFR separations are governed by FAA regulations and are set up by the ATC controller; since VFR spacings are determined almost solely by the pilot, they are not subject to the same factors as the IFR separations.

Instrument conditions below Category I (200 foot decision height and 1800 foot runway visual range) will not be considered, because of the rarity of Category II and III conditions, and because the reduced traffic in CAT II and CAT III substantially reduces the need for, and benefit of, reduced separations.

It should be realized that only the minimum IFR separations, and not the actual separations, are specified by FAA procedures. The actual separations include a buffer established by the controller in order to avoid violating the minimum separations (as will be explained in Section 4) or to avoid violation of simultaneous runway occupancy rules.

Even when reduced IFR separations are proven to be technically and operationally feasible, certain secondary factors may determine whether or not minimum separations are achieved in actual operations at a particular airport. Wet or icy runways, or the need to interleave departures, may call for interarrival separations above the minimum; the actual separations used in such cases will not change even if the minimum standards are reduced. While such factors affect the benefit derived from reduced longitudinal standards, they do not affect the feasibility of such reductions, and hence will not be considered in this analysis.

1.3 Methodology and Organization of the Report

The first step in the analysis of future separations was to achieve a thorough understanding of the relevant parts of the current ATC system. This was done by studying sources such as the Controller Handbook (Reference 5) and by observing operations at Washington National Airport (DCA). Several controllers at National were also interviewed about their control techniques and their interpretation and application of the procedures in the Handbook. Although National does not usually operate at minimum separations due to interleaved departures on the main runway, its other characteristics such as high traffic demand and absence of heavy aircraft made it a useful subject for our investigation (Appendix A contains a summary of our findings at National).

A briefing was then prepared which outlined our findings at National Airport and our thoughts at the time on reduced separations. This briefing was used as a basis for discussions with various user groups to obtain their reactions and opinions on the topic. The concerns of the user groups are discussed in Section 2 of this report.

The various factors which were thus identified were then further analyzed for severity of effect, possible procedures for easing such effects, and potential secondary effects. The most significant issue that was identified was the possibility of simultaneous runway occupancy, and the consequent need for aircraft to execute a go-around, as a result of decreased separations. This issue is more fully discussed in Section 3.

Section 4 describes the requirements which have been identified for the successful implementation of a 2.5 nmi separation standard. Section 5 describes the additional requirements and methods for the successful implementation of a 2.0 nmi standard. Some possible requirements which cannot be completely specified at this time are discussed in Section 6.

Section 7 presents a possible alternative approach to the simultaneous runway occupancy problem which might lead to earlier implementation of reduced separations at certain select locations. Finally, conclusions and recommendations are given in Section 8.

2. USER GROUP MEETINGS

2.1 Purpose of the Meetings

The initial investigation into the question of reduced separation standards, involving study of current ATC procedures and some preliminary analysis of recognized problem areas, revealed a wide range of considerations bearing on minimum separations. Not the least of these was user acceptance of any revised procedures, which would depend not only on technical analysis but also on the users' perceptions of the revisions.

Several purposes could thus be served by holding meetings with the users directly. Their reactions to our preliminary analysis could be obtained. Particular concerns which they had, based on their unique experience and operating perspective, could be learned. Additionally, an early involvement of the users would help the process of eventual implementaion.

In September 1977, a series of meetings were held separately with representatives of the Air Transport Association (ATA), Aircraft Owners and Pilots Association (AOPA), Air Line Pilots Association (ALPA), National Business Aircraft Association (NBAA), and the U.S. Air Force (a complete list of attendees appears as Appendix B). A MITRE-prepared briefing on the subject of separation standards was used at each meeting to introduce the topic. The briefing was just a springboard, however, for the wide-ranging exchange of ideas which was the primary goal of the meetings.

2.2 User Concerns

The following sections describe the concerns brought up by the users at these meetings and our current assessment of their effect on separation standards. The user concerns are divided into two categories: those which were serious enough to require significant research and investigation, and those which were relatively easy to resolve.

2.2.1 Wake Vortex

One of the first points which the briefing made was that wake vortex would not be considered as an impediment to separation reduction, since it was assumed that alternative techniques such as a Wake Vortex Avoidance System (WVAS) would provide adequate protection from vortex hazards. Nevertheless, wake turbulence was the chief concern of most of the users we spoke to. Given the

effect which wake turbulence has had on separation standards in the past, the concern expressed and the level of awareness of this problem were not suprising.

For the purpose of this study, it was assumed that wake vortices do not constrain the separation standard being investigated; in this way, the effect of other factors, not significant today but potentially limiting once the vortex problem is alleviated, can be evaluated. Of course, the effectiveness of the vortex alleviation techniques at the reduced separations will have to be thoroughly analyzed before the reduced standards can be implemented.

2.2.2 Go-Arounds

After wake vortex, the major concern of the users was the rate of go-arounds which would be required to avoid simultaneous runway occupancy. Reduced longitudinal separations would reduce the intervals between threshold crossings by successive arrivals; this would decrease the average time during which the runway was clear, following the exit of the first aircraft; and given the normal variations in interarrival times and runway exit times, would increase the chance of having two aircraft on the runway at the same time, or having a go-around to avoid such simultaneous occupancy, if no other changes are made.

Reducing runway occupancy times (ROCs) would be the most direct solution to this problem. This would be aided by exits which are well designed for location, angle and integration with the taxiway network. Greater pilot incentive to exit quickly would also help. The ALPA representatives we spoke to resisted the concept of additional pressure on the pilot, pointing out that the pilot is already in a high workload-high stress state at landing, but the incentive to exit quickly provided by another aircraft just sixty seconds behind would be undeniable.

The effects of reduced separation standards on the probability of simultaneous runway occupancy, and the requirements for keeping that probability to an acceptable level, were extensively analyzed for this report; further discussion will be found in later sections.

2.2.3 Use of Dependent Parallel Runways

One alternative to reduced ROCs which was mentioned by several different users would be the use of a close-spaced, dependent

parallel runway. This could involve either a sidestep maneuver or two separate arrival streams.

The sidestep procedure was brought up by both NBAA and AOPA, the majority of whose members fly smaller, more maneuverable aircraft. In this procedure, a single stream of aircraft would fly the approach to the main runway at reduced separations, but every other aircraft would sidestep and actually land on a second, close-spaced parallel runway. This would primarily involve the smaller aircraft, since they could execute the sidestep closer to the threshold and would require a shorter runway for landing than most air carrier aircraft.

Having the trail aircraft of a pair land on a separate runway would relieve most of the pressure on the lead aircraft to exit quickly. Reduced separations could thus be used in the air, with a corresponding capacity gain. The sidestep procedure would be less effective if alternate aircraft could not be expected to use the second runway: if, for instance, the second runway was too short for some aircraft, if there were not enough aircraft in the traffic mix which were willing to sidestep, or if weather conditions were below the sidestep minimums (generally slightly lower than for a circling approach) for some aircraft. The sidestep procedure is also authorized only for runways 1200 feet apart or less (Reference 6).

These limitations could be avoided by the use of dependent parallel approaches. Here two separate streams of aircraft use two separate close runways on an alternating basis; reduced separations would apply between the two streams, but consecutive aircraft on the same runway would have twice that separation. A similar procedure has recently been authorized for runways as close as 3000 feet (paragraph 797 of the Controllers Handbook, Reference 5).

Dependent parallel approaches could possibly be implemented sooner than reduced separations on approach to a single runway. Further discussion of this concept is contained in Section 7 of this report.

2.3 Resolvable User Concerns

In addition to the above items, several questions arose during the discussions with the users which, after investigation, were not found to be serious impediments to reduced separations. These include ILS signal interference, go-arounds by consecutive aircraft, beacon system garbling and engine exhaust effects.

2.3.1 ILS Signal Interference

Some of the user groups were concerned that ILS signal interference would be a more significant problem at reduced airborne separations. Since the trail aircraft would be closer to the lead aircraft causing the interference, it was thought that the interference would be more severe. The trail aircraft would also be closer to the threshold when the interference occurred, and therefore less able to recover the glide slope and more likely to go around. The go-around would be especially likely, almost mandatory, if the pilot were flying an autopilot-coupled approach and the ILS interference caused a decouple to occur.

There are two approaches to a resolution of this issue. The first would be to prevent the interference by keeping aircraft out of the critical areas around the localizer and glide slope antennas (Figure 2-1). Current procedures generally prohibit penetration of the glide slope critical areas if the weather is below minima and an arrival is between the final approach fix and the airport; the localizer critical area should not be penetrated in CAT II conditions (Reference 5).

The Microwave Landing System (MLS) offers the promise of smaller critical areas because microwaves are not as subject to refraction as are conventional ILS signals. The MLS critical areas derived by one study (Reference 7) are shown in Figure 2-2. The glide slope critical area is substantially smaller than the ILS area; the localizer critical area, while narrower, extends further down the runway. The final form of these critical areas and the effect of penentrating them will only be determined after future testing with an operational MLS.

The second approach to the problem of ILS interference would be to recognize and evaluate the benefits of reduced separations in this situation. Current airline procedures call for a go-around from a coupled approach if decoupling occurs, but only if the approach cannot be continued visually. Reduced airborne separations could actually lead to a reduction in the number of go-arounds due to decoupling, because the trail aircraft will be closer to the runway and more likely to have established visual contact should a decoupling occur.

2.3.2 Go-Arounds by Consecutive Aircraft

If a departure or a go-around flies over the localizer antenna, there might be a momentary flicker of the localizer signal. This flicker is not expected to cause an autopilot decouple, but if it

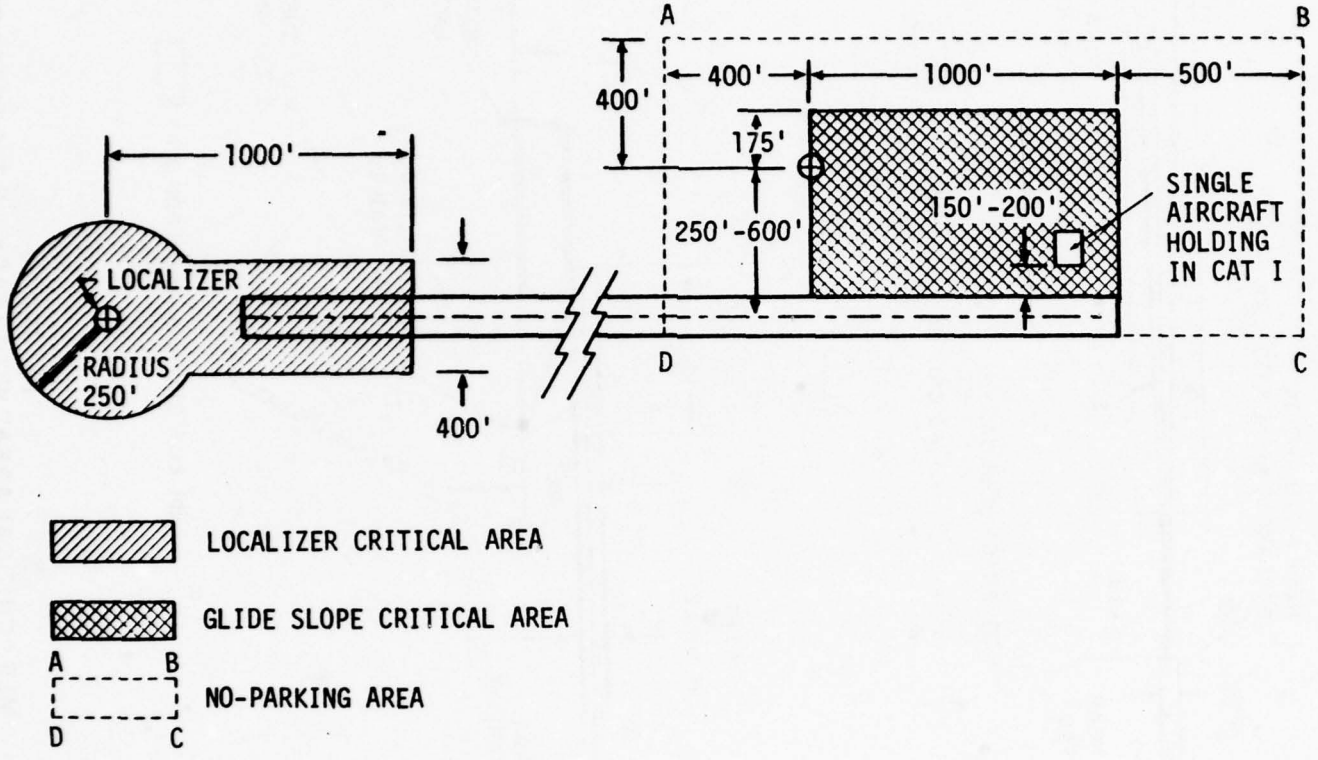
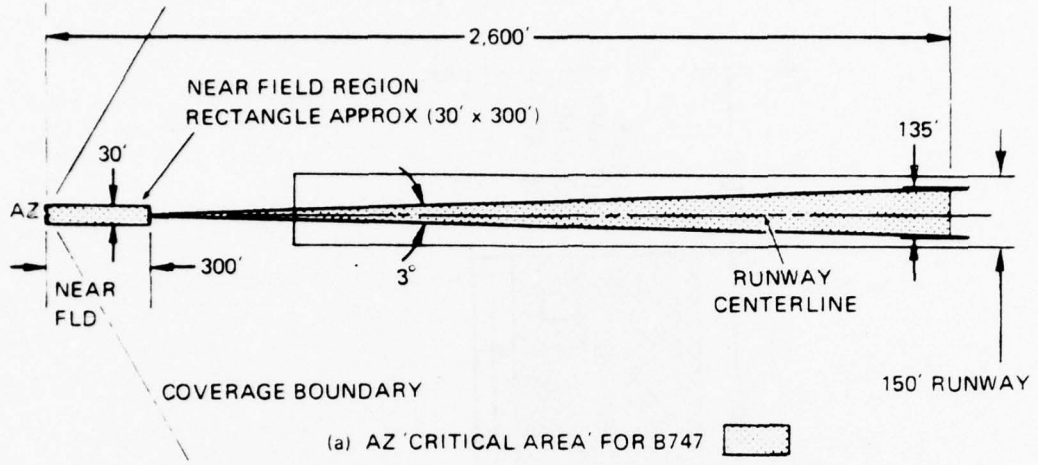
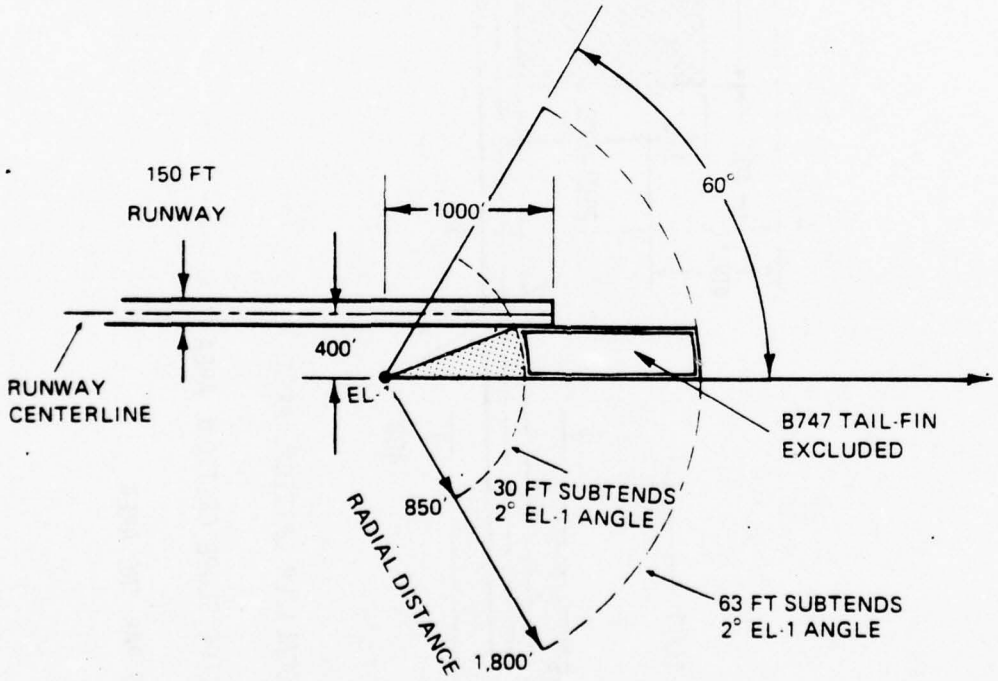


FIGURE 2-1
ILS CRITICAL AREAS



(a) AZ 'CRITICAL AREA' FOR B747



(b) EL-1 'CRITICAL AREA' FOR B747

FIGURE 2-2
MLS "CRITICAL AREA" WITH TRACKING TYPE PROCESSOR

should, there could be a situation where two aircraft were on the go-around track simultaneously. Some of the users were concerned that this could lead to midair conflicts.

In analyzing the general situation, it was determined that three separate types of incidents could occur, depending on which aircraft in the pair went around first (Figure 2-3). If the lead aircraft goes around first (Case A), acceleration to climb speed will increase the separation between the aircraft, regardless of when the second aircraft starts its go-around.

If both aircraft go-around simultaneously (Case B), longitudinal separation will be maintained in the climb. However, since the trail aircraft started at a higher altitude, it will level off first and decrease the separation until the lead aircraft also levels off. The controller can avoid a conflict by assigning different altitudes or requesting an appropriate speed change.

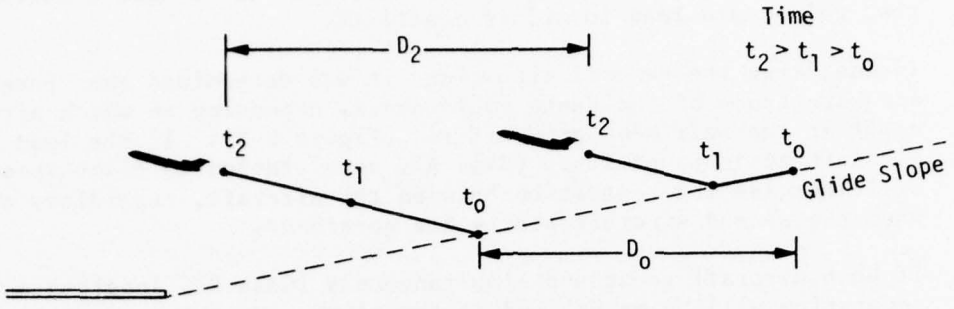
In Case C, the trail aircraft goes around first. Longitudinal separation may decrease, but altitude separation can usually be established as long as both aircraft are climbing. Since the trail aircraft will reach the go-around altitude even earlier now than the lead aircraft, the separation between the two will be even less in this case when the lead aircraft does level off. Once again, controller action will be necessary.

It is extremely unlikely that the necessary action would not occur in time to avoid a conflict. One reason is that a double go-around currently is such a rare event that it would certainly be noticed and closely monitored by the controller. Another reason is that ample time exists, even at reduced separations, to resolve the potential conflict. Assuming a 100 kt. closing speed between the two aircraft as a worst case, it takes 108 seconds to cover 3.0 nmi and 72 seconds to go 2.0 nmi.

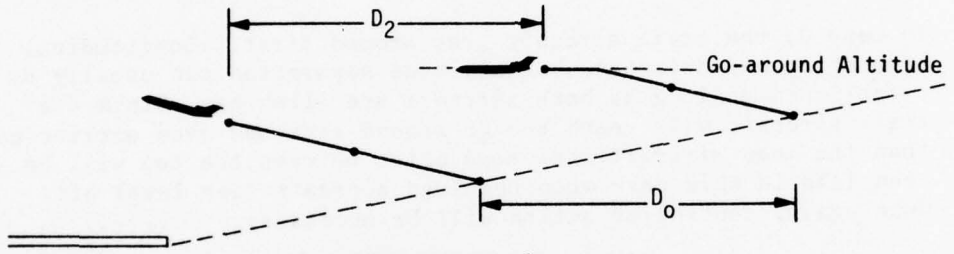
If a double go-around were to occur, controller action to prevent a conflict would be required even today. The only effect of reduced separations would be to reduce the time available for the controller to take action, although ample time would still remain.

2.3.3 Beacon System Garbling

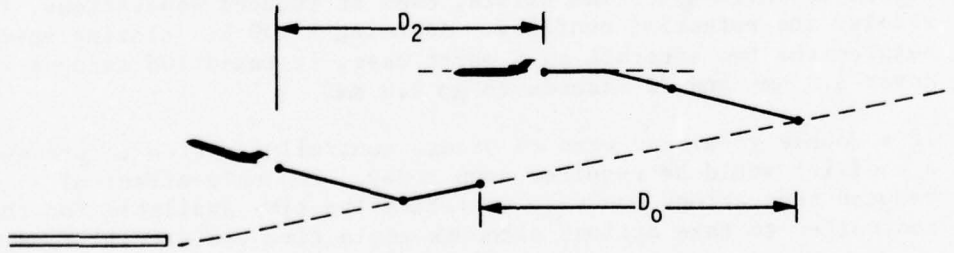
The question has also been asked whether the present radar and processing systems can accurately distinguish between two aircraft flying at reduced separations. A previous MITRE report (Reference 3) included a theoretical analysis of this question,



A. LEAD AIRCRAFT FIRST ($D_2 > D_o$)



B. SIMULTANEOUS ($D_2 = D_o$)



C. TRAIL AIRCRAFT FIRST ($D_2 < D_o$)

FIGURE 2-3
GO-AROUNDS BY CONSECUTIVE AIRCRAFT

based upon the technical characteristics (especially the allowable performance variations) of transponders and the ATCRBS system. The result of this analysis was that garbling was not expected until the aircraft were 1.48 nmi apart if the radar antenna was approximately centrally located on the airport, or 2.28 nmi if the radar were 20 nmi to one side of the arrival track (a worst case assumption).

This worst case corresponds to the actual situation at San Francisco, where the Airport Surveillance Radar is located across the bay in Oakland. Discussions with the SFO tower, however, revealed that no cases of garbling are observed, even when the aircraft are virtually side-by-side on a VFR parallel approach (about 700 ft. apart). Some radar target overlap might occur, but the speed differential between the aircraft will quickly open the gap to one-half to one mile. At these separations, the aircraft are easily distinguishable, according to the SFO operations officer.

The theoretical analysis thus seems to be extremely conservative. If beacon garble is not a problem in reality at San Francisco, it seems unlikely that it will be a problem elsewhere.

2.3.4 Engine Exhaust Effects

A question was asked in one of the user group meetings about the possible effects of engine exhaust on the trail aircraft at reduced separations. The concern was that the engines would lose power if they ingested the exhaust of the previous aircraft, since less oxygen would be available. This point apparently came up first during an internal ATA study; it was not considered a serious problem at the time, and there is no reason to disagree now.

There are several methods whereby the engine exhaust is dissipated and diluted long before it reaches the trail aircraft. In addition to wind motion, there are also turbulence behind the wings and around the fuselage, and the design of the turbofan engine, which mixes ambient air from the fan with the hot exhaust from the turbine.

In addition, several conversations with FAA Flight Standards and with the U.S. Air Force have uncovered no examples of such exhaust effects ever actually occurring, not even at the extremely close spacings involved with the Air Force's inflight-refueling and formation flying exercises. It thus seems reasonable to dismiss this question as a factor at 2.0 nmi spacings.

3. GO-AROUNDS TO AVOID SIMULTANEOUS OCCUPANCY

3.1 The Importance of the Go-Around Rate

Paragraph 1120 of the Controller's Handbook (Reference 5) generally prohibits two landing aircraft from occupying the same runway at the same time. Exceptions are allowed, but only during daylight hours, with good visibility, if neither aircraft is an air carrier (12,500 pounds or over). Since these conditions are contradicted by the basic assumptions of this analysis (IMC and air carrier operations), we shall assume that simultaneous runway occupancy is prohibited.

Of course, the easiest way to eliminate the problems caused by go-arounds to avoid simultaneous runway occupancy would be to simply allow simultaneous occupancy. Some restrictions would still be required to limit the chance of a ground collision: the first arrival would have to be a minimum distance down the runway, for instance, when the second arrival was over the threshold or some other point. In our judgement, however, the risk to fare-paying passengers would make such a procedure unacceptable for air carrier aircraft. Even if the simultaneous occupancy rule were relaxed, occasional go-arounds would still be required, to avoid violating the new procedure. Changes to the simultaneous occupancy rule were, therefore, decided to be of doubtful overall benefit, and will not be considered in this analysis.

The controller has several technques available for avoiding simultaneous runway occupancy; a go-around is usually only the last resort.* Either the controller or the pilot can initiate a go-around. Unless he receives control instructions otherwise, the pilot will then follow the published missed approach procedures, which will take him to a holding fix from which another approach can be attempted. The go-around aircraft has no particular priority but must be fitted back into the arrival stream as best the controller can. A go-around can thus lead to significant delay and fuel expense.

As discussed in Chapter 2, the user groups were concerned that reduced separation standards could cause an unacceptable increase in the rate of go-arounds required to avoid simultaneous runway occupancy.

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*Note that the term "missed approach" refers to an instrument approach which cannot be completed, usually caused by poor visibility. "Go-around" will be used herein to refer to all other causes of abandoned approaches.

Our analysis showed the go-around rate to be the most significant factor affecting the feasibility of reduced IFR separation standards, after wake turbulence effects. Not only is the go-around rate itself a significant factor, but both the problem and its potential solutions have indirect effects on the other concerns raised by the users.

3.2 Go-Arounds and ATC

Go-arounds are rare in today's ATC system. There are many opportunities for controller intervention to adjust the separations between aircraft prior to the final approach in order to avoid the need for a go-around. For one thing, initial spacings include a buffer above the minimum separation. If this buffer is inadequate, or if the aircraft begin to close together, the controller will usually ask for a speed change. The limited speed range available to aircraft in the terminal area, and the limited time available for the speed change to be effective, prevent any great change in the spacing, but it is often enough to avoid a violation of the standards.

The controller also uses path-stretching, vector spacing and path-shortening to regulate separations, such as by varying the point on the downwind leg where an aircraft is turned onto the base leg. In extreme cases, he may even ask small aircraft to do a complete 360° turn, if possible.

Once the aircraft is on the final approach, there is little that can be done to control spacings. Aircraft following an ILS can vary their speed only slightly and their flight path not at all. If the airborne separations were not accurately judged, or if the lead aircraft takes unexpectedly long to exit, a go-around is the only available course of action.

The controllers at National Airport indicated that they preferred to give the go-around command by the time the aircraft was about one-half mile from the runway threshold. This is a typical missed-approach point for an ILS approach; the pilot is still not totally committed to a landing and can reconfigure the aircraft and start his go-around climb more easily than if he were closer. (This should not be taken to mean that an arrival can never pass the half-mile point if the previous aircraft is still on the runway -- instead, the controller uses his judgment and experience to estimate whether that arrival will still be on the runway by the time the next aircraft would cross the threshold. If not, no go-around will be called.)

Controllers, like pilots, would prefer to avoid go-arounds completely if at all possible. Go-arounds are rare enough that separate airspace is not reserved for them; this means that other aircraft must be maneuvered away from the missed approach course and their normal flight paths, requiring special coordination between the arrival and departure controllers. And the go-around requires special attention to be merged back into the arrival stream.

To minimize the chance of a disruptive go-around, the controllers add extra margins to their operations. An actual separation is aimed for which is greater than the minimum by a certain margin; this buffer helps compensate for speed differentials, control uncertainties and measurement errors,* to keep the actual separations above the minimum. The controller can also increase this buffer if necessary to interleave departures between the arrivals, or if the runways are wet or icy. Reducing the minimum separations would not affect the actual separations used in special cases such as these, but the actual separations used normally should decrease if a capacity increase is to result.

3.3 Required and Actual Intervention and Go-Around Rates

If the actual separations are larger than the minimum by some buffer, what determines the size of the minimum? Instead of, for example, a 3.0 nmi minimum and a 1.0 nmi buffer, why not decide arbitrarily that the minimum is 1.0 nmi and the buffer is 3.0 nmi? Actual separations would be unchanged. However, one criterion for establishing a minimum separation is that actual operations could be conducted at the minimum separation for extended periods of time without unacceptable results. Actual separations of 3.0 nmi would be feasible, but 1.0 nmi would not.

Associated with the minimum separation is a maximum allowable runway occupancy time, the largest time an aircraft can remain on the runway before the next aircraft would be required to go around. A 1.0 nmi minimum is not feasible because the required average runway time of about fifteen seconds could not be achieved. A "reference runway" can be postulated to illustrate this concept.

*Controllers measure separations indirectly by comparing the distance between targets on the radar screen with a known distance, such as the five mile range rings. Three miles is thus "a little more than half the distance" between the rings.

We assume that two arrivals are separated by the IFR minimum of 3.0 nmi. Both have a final approach speed of 140 knots; most commercial aircraft today, with the exception of the Concorde and some high-weight versions of the B747, have a speed over threshold of 140 knots or less at sea level (Reference 8). It is also assumed that Runway Occupancy Time (ROC) is normally distributed, with mean μ_R and standard deviation σ_R.

A go-around will be required when runway occupancy is greater than the time before the next arrival crosses over the threshold (interarrival time, IAT), that is, if ROC > IAT. This can also be expressed as (IAT - ROC < 0) -- the time gap between the first aircraft exiting and the next passing over the threshold is negative.

To keep the number of go-arounds low, the average ROC must be less than IAT by a certain buffer. If we accept a 5% violation rate on ROC for planning purposes,* the buffer would be equal to 1.65 σ_R, or 14 seconds (σ_R = 8.4 seconds).** Since the IAT is 77 seconds (3.0 nmi at 140 kts), this implies that 63 seconds (77s - 14s) is the maximum average ROC compatible with a 3.0 nmi minimum.

Figure 3-1 demonstrates the "reference runway" concept. Given the normal distribution of ROC, 5% of the individual ROC events will be greater than the IAT of 77 seconds only if the average ROC is 63 seconds.

Most average ROCs today are well below 63 seconds, so the use of the 3.0 nmi IFR minimum is usually not limited by runway occupancy. Average ROC for Runway 26R at Denver, for example, is 51.5 seconds. An extreme case, Runway 22R at O'Hare, has an average ROC of 63s (Reference 10) due to exit location, which would seem to make a 3.0 nmi standard just barely feasible; according to tower personnel, the interarrival separations do, in fact, have to be increased as soon as the runway becomes wet and average ROC increases. This lends credence to the "reference runway" concept.

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*See Reference 11. This is the same violation rate as has been observed for IAT in the current ATC system.

**This value of σ_R was obtained from data collected at Denver Stapleton International Airport for Runway 26R, which was chosen as a typical runway for this analysis. For additional information, see Appendix C or Reference 9.

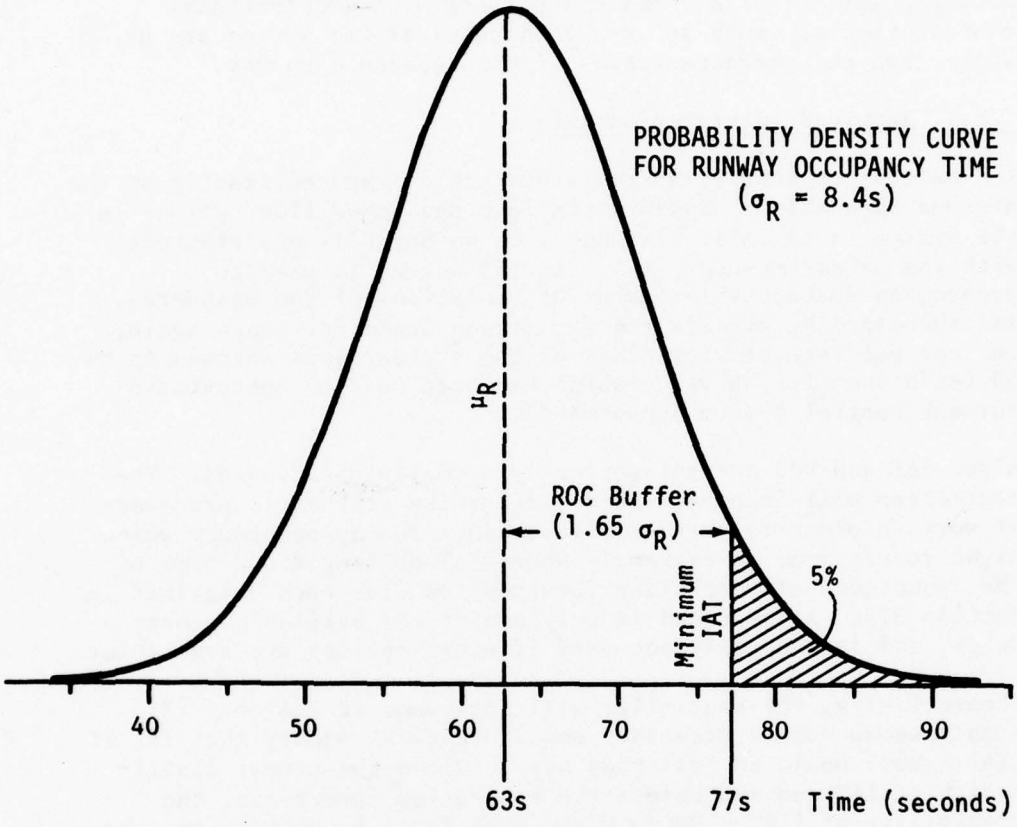


FIGURE 3-1
THE REFERENCE RUNWAY

This reference runway is based upon observed characteristics of actual operations in today's ATC system, such as runway 22R at O'Hare. It represents a real world situation which is acceptable to both pilots and controllers. The following analysis of reduced longitudinal separation standards is based upon the assumption that a future ATC system with reduced separations will also be acceptable to pilots and controllers if the operational characteristics (such as go-around rate) of the system are no worse than the characteristics of the reference runway.

3.3.1 Required Intervention Rate

In reality, of course, arrivals are not all spaced exactly at the minimum separation. Speed variations and other fluctuations in the system cause IATs, like ROCs, to be normally distributed, with the parameters (μ_I, σ_I). An IAT buffer is used to prevent an unacceptable number of violations of the standards, and therefore μ_I exceeds the separation standard. Once again, the nominal rate of violations of the standards is assumed to be 5% (Reference 11), a value which has been used to approximate current control system performance.

Also, IAT and ROC are not perfectly normally distributed. The controller will intervene in the otherwise stochastic processes at work in order to prevent simultaneous runway occupancy which might result from an extremely short IAT or long ROC. Some of the techniques of controller intervention have been described in Section 3.2. A go-around is only one of the available procedures, and is generally not used if other options are available.

Theoretically, the controller will intervene if and only if simultaneous runway occupancy would otherwise occur, that is, if (IAT - ROC) would be less than zero. Given the normal distribution of IAT and ROC before the controller intervenes, the probability of (IAT - ROC) < 0 and therefore, by definition, the required intervention rate, are easily calculated.

The mathematical derivation of the required intervention rate is detailed in Appendix D. Since ROC and IAT are normally distributed, the difference between them (IAT - ROC) is also normally distributed, with a mean of ($\mu_I - \mu_R$), and a standard deviation equal to the square root of ($\sigma_I^{\,2} + \sigma_R^{\,2}$). This resulting curve can be described by standard normal distribution tables. See Figure 3-2.

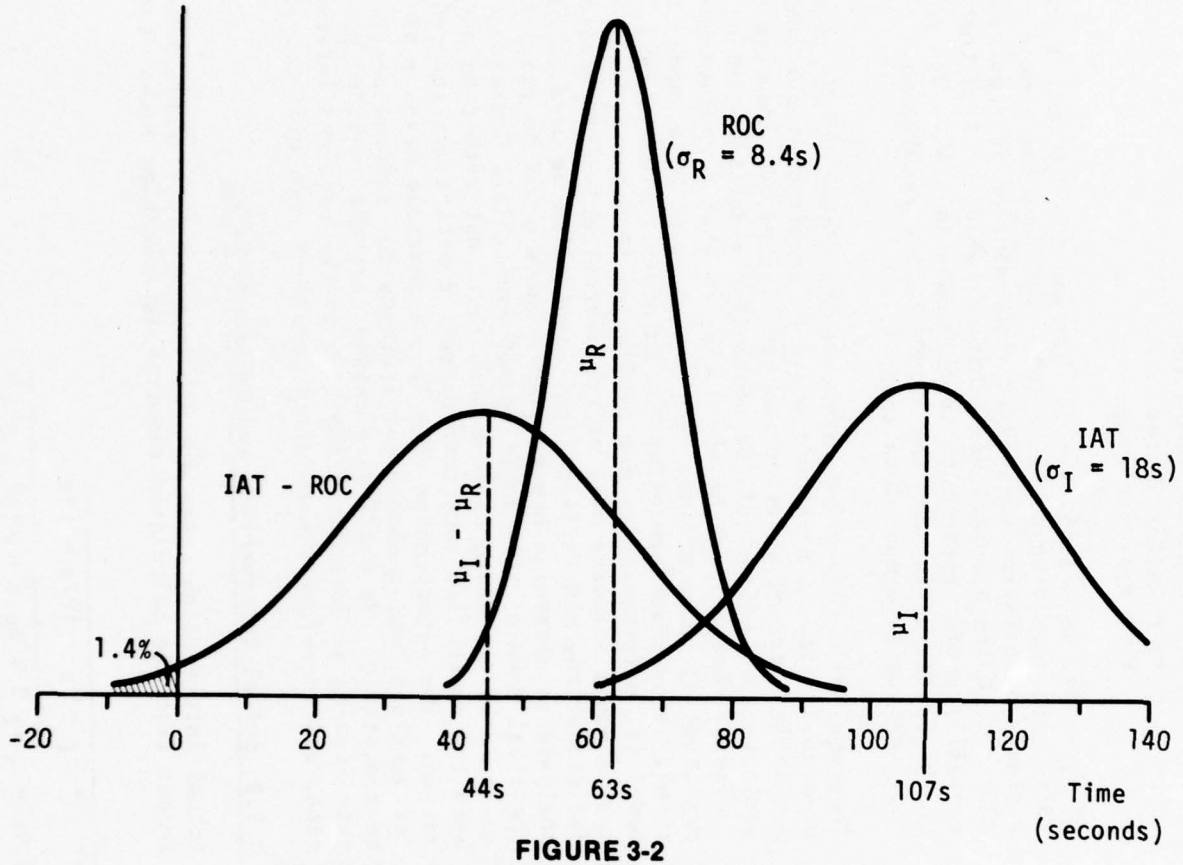


FIGURE 3-2
PROBABILITY DENSITY CURVE FOR (IAT - ROC)

In the reference runway example, σ_R = 63s and σ_R =8.4s. Mean IAT is defined as

$$\mu_I = \frac{3600 * S}{V} + z_I \sigma_I$$

where S = minimum separation
z_I = buffer factor
V = approach speed

If σ_I = 18s, z_I = 1.65, V = 140 kts and S = 3.0 nmi, then μ_I = 107s. The resulting curve of IAT - ROC thus has a mean of 44s and a standard deviation of 19.9s.* Intervention is required if (IAT - ROC) < 0. Using a normal distribution table, we find that the net probability of intervention in this case is 1.4%. The combination of the 5% IAT buffer and the 5% ROC buffer results in a required intervention rate much less than 5%.

The required intervention rate contains within it the required go-around rate. A go-around would be required if all other available forms of intervention have failed; determining this rate would require a model of the controller's decision making process, including what actions he would take in what circumstances and the magnitude of those actions (e.g., a 10 kt or 20 kt speed reduction), to estimate how often the intervention would fail. Such a model is, unfortunately, not available. A Metering and Spacing system would automate most of the controller's intervention decisions; the M&S decision logic could also be used in this analysis to determine how many go-arounds would be required, but the final form of this logic is not available. Consequently, this analysis is not based on go-around rate, but rather on the need to keep the controller intervention rate constant for reduced separation. The intervention rate is one possible measure of controller workload, which should not increase for reduced separations to be acceptable. We shall also assume that the required go-around rate remains in constant proportion to the required intervention rate, and therefore the required go-around rate will not increase.

3.3.2 Actual Intervention and Go-Around Rates

Actual intervention rates are not expected to be greatly different from the calculated required intervention rate. The

* 44s $= \mu_I - \mu_R = 107s - 63s$

$19.9s = \sqrt{\sigma_I{}^2 + \sigma_R{}^2} = \sqrt{18^2 + 8.4^2}$

difference would be due to the controller's inherent caution and his lack of perfect knowledge. In other words, he would prefer to intervene with a possibly-unnecessary speed reduction when the aircraft is far from the runway, rather than risk simultaneous runway occupancy, separation violation, or a go-around to avoid these situations, later. And he can only use information on the present position and speed of the aircraft, and his own experience, to assess that risk.

No reliable information on actual intervention rates or even actual go-around rates is available. To our knowledge, no survey of controller intervention has ever been attempted.

Some information on actual go-around rates is available from an FAA survey of abandoned approaches (approach attempts which were broken off for reasons of weather, safety, etc.) which was conducted during the first three months of 1974 (Reference 12). Reports from the field controllers were the principal data source. However, the results were incomplete. The survey indicated that 1.9% of the IFR approaches during this period were unsuccessful, but these appear to be predominantly weather-related missed approaches. The percentage of ATC-initiated go-arounds was only .09%. For the one month for which the reasons for these go-arounds were reported, there were 126 ATC-initiated missed approaches; only 40 missed approaches, out of 74 for which a cause was reported, involved inadequate interarrival separations.

Subjective estimates of the rate of abandoned approaches are also available. One controller at National Airport estimated the frequency of go-arounds there as one per shift; another said one per day. An informal survey of professional pilots led to an estimated rate of one per 2600 operations (Reference 13).

Such subjective estimates must be approached with caution, of course, but they do tell us one thing: it would take a survey team a very long time to collect data on a significant number of go-arounds. This tends to make a special go-around survey impractical. The controller himself could be asked to record the go-around data, but such events tend to occur when traffic is heaviest and the controller busiest at his primary job of moving airplanes. The complete set of information on actual go-arounds which would be of interest is quite extensive. Some thoughts on the requirements for a complete go-around survey are given in Appendix E.

A survey of controller interventions would perhaps be easier to perform, but would require skilled observers who would be able to distinguish interventions to avoid simulation runway occupancy from interventions for other reasons. Nonetheless, such surveys should be considered, to validate the theoretical analysis herein.

4. REQUIREMENTS FOR 2.5 NMI SEPARATION STANDARDS

4.1 Runway Occupancy Time

4.1.1 Maximum Average ROC

In the previous chapter, the concept of the "reference runway" was described. A maximum average runway occupancy time was determined which would allow continuous operations based upon the minimum separation standard. For a 3.0 nmi standard, this meant that average ROC had to be 63 seconds or less.

The same procedure could be used to calculate the maximum average ROC for a 2.5 nmi IFR standard. IAT would be 64 seconds at 140 knots, and subtracting the 14 seconds ROC buffer would give 50 seconds. Assuming that nothing else changes in the reference runway example, reducing the minimum separation by 0.5 nmi would require that the maximum average ROC must also be reduced, by the amount of time it would take to fly that 0.5 nmi, in order to keep the go-around rate and other operational characteristics constant. The effect would be as if a 13 second slice were removed from the previous 3.0 nmi scenario.

4.1.2 Actual Field ROC

Whether or not 50 seconds is an achievable mean ROC depends upon the runway involved. A recent analysis of runway occupancy data (Reference 9) suggests that such ROC levels are well within the capability of aircraft today. This analysis has been summarized as Appendix C.

The observed data produced mean ROCs ranging from 51 seconds to 41 seconds for aircraft of the DC9 - 727 class, and 58 to 51 seconds for larger jets (see Table 4-1). For the smaller jets, at least, it would seem that the ROCs required for 2.5 nmi are feasible today. Most of this data was, however, collected in VMC (Visual Meteorological Conditions) and is therefore of limited applicability to IFR conditions. VMC runway occupancy times are expected to be lower than those in IMC (Instrument Meteorological Conditions) today, because pilots exercise greater caution in exiting the runway when their visual references are limited. Another reason may be that, since visual separations are frequently less than the minimum IFR spacings, there is more pressure on the pilot to exit promptly. If IFR spacings are reduced, this same effect may tend to reduce the IMC occupancy times. Unfortunately, the exact difference between VMC and IMC occupancy

TABLE 4-1

RUNWAY OCCUPANCY TIME DATA

	Runway	Mean ROC (Seconds)	Standard Deviation (Seconds)	Number of Records
Group 3 (BAC 111, DC-9, 737, 727)	ATL 27R (26)	51.4	7.5	97
	BUF 5	50.7	13.8	33
	BUF 23	55.9	8.7	124
	DEN 26R*	51.5	8.4	314
	LAX 25L	48.2	10.4	98
	LAX 25R	52.6	14.1	138
	LGA 22	43.3	9.5	315
	LGA 31	40.7	8.5	103
	SFO 28R	47.4	9.2	93
	SFO 28L	49.3	8.1	138
Group 4 (707, DC-8, L1011, DC-10, 747)	DEN 26R*	55.1	9.4	100
	LAX 25L	50.9	9.6	150
	LAX 25R	60.2	16.8	50
	SFO 28R	57.5	16.5	61
	SFO 28L	55.0	13.4	130

*DEN 26L closed during survey period

times is not known. Although the relative rarity of true IFR conditions and the observation problems in low visibility make IMC data collection difficult, information on runway occupancy times in IFR conditions is essential for a complete evaluation of IFR separation standards. (Note that wet and icy runways should be excluded, since separations greater than current minimums are frequently used in such cases; reducing the minimum spacing would thus not affect capacity.)

One other caveat must be mentioned in reference to the data. Many data points were discarded because of obvious errors such as negative occupancy times. Other data were questionable, but an adequate case could not be made for eliminating them. There exists, therefore, the possibility that some of the other data contains errors which could not be recognized. The possibility of errors in the data must, therefore, be considered, although every attempt was made to minimize their effect.

4.1.3 Potential for ROC Reduction

Reference 9 also describes how the available data was analyzed by air carrier, and how a correlation was found between the position of that carrier's gates and the exits used by its aircraft. Pilots tended to minimize their total time traveling to the gate, even if this entailed a runway occupancy which was greater than normal. The difference in average ROCs between those carriers which were presumed to be motivated to exit early and those which were not was as much as 8 seconds. One means to reduce average ROC might, therefore, be to increase the general level of pilot motivation: either airlines could change their procedures, to emphasize to pilots the desirability of an early exit despite the extra brake and tire wear, or else the motivation could come from the reduced spacings themselves.

In a few cases, additional exits could be provided which would naturally be more convenient for the pilot to use and which could therefore reduce ROCs. But at most major airports today, the convenient exits already exist. New exits could be built, either high speed or conventional, which would reduce ROCs if used, but the actual use of these exits would depend on two factors: motivation, as discussed above, and design, in terms of proper turn-off angle, pavement surface, and integration with the taxiway system so that the pilot was willing to use the exit.

Integration with the taxiway system means that the pilot can taxi to his destination simply and directly, with a minimum of delay. It also means that the aircraft taking a high-speed exit does not require extreme deceleration in order to negotiate a sharp turn on the taxiway or to avoid colliding with other aircraft. Before a pilot will make a high-speed exit, he will probably require some guarantee that the taxiway is clear of other aircraft for a reasonable distance. This will require either adequate visibility conditions for the pilot, or surface monitoring equipment in the tower and good communication between controller and pilot. Lack of such a guarantee would mean that the high-speed exit would not be used, but instead a later exit with a slower turn-off speed would be chosen. In this analysis we have assumed IMC, but no worse than Category I minima of 1800 feet runway visual range. This allows the pilot to see 20 seconds ahead at 50 kt, or 36 seconds at 30 kt, which should allow confident exiting at reasonably high speeds.

Consistent use of high-speed exits might also require advance clearance to taxi, delivered before the aircraft exits. Currently this clearance is not delivered until the aircraft switches to ground control at the time of exiting; channel congestion or other failure to get immediate clearance means that the pilot must come to a full stop until clearance is obtained. This possibility reduces the incentive for early exiting.

A substantial number of aircraft in the survey were observed using high-speed exits as close as 4300 feet and conventional exits as close as 4500 feet to the runway threshold. If such exits were available and used at all airports, average runway occupancy times would be about 40s. Even without new exits, ROC reductions as great as 14s could be obtained if aircraft would regularly use the first feasible exit, i.e., the first exit currently available which is located more than 4300/4500 feet from the threshold.

4.2 Other Requirements

It thus seems that the 50 second runway occupancy requirement for implementation of a 2.5 nmi separation standard can be met. Most runways studied were at this ROC level or below presently, and procedures are available for bringing the remaining runways into line as well. A 50 second ROC should result in a reasonable and acceptable go-around rate.

The other requirements for reduced separation standards are fairly straightforward. In order to avoid calling unnecessary go-arounds at the lower separations, the controller needs continuous surveillance of the approach path and runway, at least from the middle marker inbound. This may be visual or radar coverage or a combination thereof. Unless the controller knows where the aircraft are, additional buffers would be needed to compensate for the uncertainty.

Adequate surveillance of the taxiway network will also be required, in order to assure the pilot that a safe, early exit is possible, and also to handle the higher traffic levels allowed by reduced separations. Surveillance may be visual or by radar (ASDE or ASTC).

Otherwise, no special equipment or procedures are required, merely the reemphasis of current procedures. This applies particularly to the need to keep taxiing aircraft out of the ILS critical area, although reducing runway occupancy time will also help to clear aircraft off the runway before they can penetrate the localizer critical area.

It is not expected that any special procedures will be required to handle the increase in traffic resulting from a 2.5 nmi separation. This should increase the number of aircraft per sector in the terminal area by no more than one or two; resectorization is possible if it is felt that this is an unacceptable increase. The maximum number of arrivals handled by the tower controller would increase from four with a 3.0 nmi standard to perhaps five at 2.5 nmi (assuming a ten mile final). The effects of reduced separation on controller workload depend upon other factors in the ATC system (operational procedures, equipment capabilities, aircraft performance) in effect when the separation reduction is implemented. Thorough testing and analysis will be required to be sure that controller workload will not be unacceptable.

There was a question early in the study about the effect this increased traffic might have on radio traffic on the tower frequency. Of particular concern was the possibility that a go-around command could be significantly delayed by an unusually long, or even a normal length, pilot message. Appendix F presents an analysis of the communications problem in the terminal area. In IMC, messages from the aircraft were observed to utilize the voice channel only 12% of the time, leaving it available to the controller the remainder of the time. Of these messages,

99% were 6.5 seconds or shorter. The expected waiting time for the go-around message appeared, therefore, reasonable and within the assumptions of the analysis.

4.3 Conclusion

In cases where wake vortices are not a limiting factor, a reduced standard of 2.5 nmi appears achievable today at some airports. Additional airports (runways) could be made to qualify for operations at 2.5 nmi by taking measures to reduce runway occupancy time. These actions could be taken without implementing any other improvements.

Otherwise, no special procedures or equipment are expected to be required. In certain cases, it will be necessary to reemphasize current procedures and good operating practices. Additional research will be required in the area of controller workload and communication channel loading.

5. RUNWAY OCCUPANCY REQUIREMENTS FOR A 2.0 NMI SEPARATION STANDARD

It was decided early in the project that an analysis of the entire spectrum of possible separation standards would be neither feasible nor necessary. Because the human controller gauges separations by comparing them with known distances, he cannot recognize small differences in spacings. Only two values of reduced separations have been considered, 2.5 nmi and 2.0 nmi. Controllers estimate the current 3.0 nmi minimum as being "slightly more than half" of the distance between adjacent 5 nmi range marks on the radar screen, so these reduced separations would correspond to "exactly half" and "slightly less than half," respectively. Further automation features could, of course, improve the resolution of these distances, but it still seems reasonable to limit analysis to the two likely steps of 2.5 and 2.0 nmi. Separations below 2.0 nmi were felt to be too remote from present-day experience to be analyzed by comparison with the current system.

5.1 Maximum Average ROC

The 2.5 nmi standard was analyzed in the previous section where it was determined that a 50 second mean ROC would enable operations at this separation. Following the same "reference runway" logic for a 2.0 nmi IFR standard for air carrier aircraft would require that this mean ROC be reduced by an additional 13 seconds, to 37 seconds, to allow operations at the reduced standard.

This average ROC, the maximum which would be compatible with a 2.0 nmi standard, is lower than that reported in Reference 9 for air carrier aircraft at any airport surveyed. Possibly this level could be achieved at some airports if the necessary modifications were made to the runways, taxiway networks and operating procedures. But it is doubtful that such an average ROC could be maintained for any great length of time, especially in IFR weather. Methods other than reduced ROC alone would, therefore, be required to make a 2.0 nmi standard feasible,* or

*ROCs for individual aircraft could be reduced by such improvements as automatic braking systems or reduced landing speeds. The Terminal Configured Vehicle (TCV) program at NASA Langley is testing such useful concepts as exiting and taxiing guidance under reduced visibilities, which would benefit ROCs. Despite the benefits of such improvements, it is our opinion that there would be a long delay before a significant fraction of the fleet was so equipped; such modifications will, therefore, not be further considered in this report.

even to realize the 2.5 nmi standard at certain airports where the ROCs cannot be reduced to the degree described in the previous section.

5.2 Standard Deviation of Runway Occupancy

One beneficial side effect of reducing runway occupancy has not yet been discussed. Reducing the mean ROC will probably result in a reduced standard deviation of the ROC (σ_R) as well. Reducing the standard deviation reduces the buffer which must be placed on runway occupancy times.

As an example of the reduction in σ_R, consider the case of a runway with just two exits, one at mid-field and the other at the far end. If all aircraft used the mid-field exit, the average ROC would be decreased by the elimination of the long rollout to the end of the runway. At the same time, the range and the standard deviation of the observed ROCs would decrease.*

For the purposes of this analysis, we will assume that σ_R can be reduced by about one-third, from 8.4 to 6.0 seconds. In our judgment, this is a reasonable value. A 5% buffer on ROC would then be 10 seconds, and the reference runway would yield a 41 second maximum average ROC. Maintaining the current intervention rate of 1.4% as delineated in Section 3.3, however, would require a 39 second mean ROC. This is determined as follows (for details and notation, see Appendix D):

$$\phi(z)_{IN} = 1.4\%$$

$$z_{IN} = 2.19 = \left| \frac{x - \mu}{\sigma} \right|$$

$$2.19 = \left| \frac{0 - (\mu_I - \mu_R)}{\sqrt{\sigma_I^2 + \sigma_R^2}} \right|$$

$$\mu_R = \mu_I - 2.19 \sqrt{\sigma_I^2 + \sigma_R^2}$$

$$= 81 - 2.19 \sqrt{(18)^2 + (6)^2}$$

$$= 39 \text{ seconds}$$

*In this case, ROC would probably be a double-peaked, rather than a normal, distribution. Most runways at major airports have numerous exits, so that the assumption of a normally-distributed ROC is fairly accurate as well as a useful approximation.

It may not seem that the effect of the σ_R reduction is very substantial; 39 seconds is not that much different from the 37 second value previously derived. But mean ROCs not much greater than 39 seconds have been observed at LaGuardia (see Table 4-1), so there is a possibility that the runway performance needed to implement a 2.0 nmi standard without further change in the ATC system would be feasible at a few airports today.

5.3 Standard Deviation of Interarrival Time

The above equation for the intervention rate also includes σ_I -- the standard deviation of the Interarrival Time. It is present in the equation both directly and, as a factor in determining buffer size, indirectly through the mean IAT.

The data used to derive the value of σ_I for today's ATC system was collected during heavy traffic periods, when it could be assumed that there was a continuous supply of arriving aircraft and, consequently, all interarrival separations were close to the minimum. The standard deviation of the interarrival times, therefore, was solely a function of the accuracy of the ATC system. A reduction in σ_I would be desirable; with improved control over the arrivals, the average spacing could also be reduced, since the separation buffer would no longer need to be so large. Capacity would consequently increase and delays would be reduced.

5.3.1 Automated Metering and Spacing

Automated Metering and Spacing (M&S) analyzes the data available through the ARTS III terminal radar, constructs commands which are designed to deliver the aircraft to the threshold at a specific time, and presents the commands to the controller for relay to the pilot. The best current estimate is that an automated M&S system would reduce σ_I from its present value of 18s to 11s (Reference 11).

Automated M&S will also recognize when a violation of standards is about to occur and will notify the controller accordingly. It is not expected that the controller will have as good a "picture" of the air traffic situation with M&S as he had previously because he will not be as involved in the decision-making process. As a result, he will not be able to react as quickly or as well to a potential separations violation situation. In order to keep overall safety levels high, the design for M&S includes the use of larger 1% buffers on IAT (equal to 2.33 σ_I) rather than the current 5% buffer (1.65 σ_I).

5.3.2 Effect on Maximum Average ROC

These two characteristics of automated M&S, the 11s σ_I and the 1% buffer, have the net effect of increasing the maximum average ROC which would be compatible with a 2.0 nmi separation. By the method derived in Appendix D:

$$\Phi(z)_{IN} = 1.4\%$$

$$z_{IN} = 2.19 = \frac{\mu_I - \mu_R}{\sqrt{\sigma_I^2 + \sigma_R^2}}$$

$$\mu_R = \mu_I - 2.19 \sqrt{\sigma_I^2 + \sigma_R^2}$$

$$= \left[51.4 + (2.33 * 11)\right] - 2.19 \sqrt{(11)^2 + (8.4)^2}$$

$$= 77 - 2.19\ (13.8)$$

$$= 47 \text{ seconds}$$

This 47s value is a substantial improvement over the 39s previously required. And if a reduced σ_R is considered as well, the required mean ROC is as high as 50s, for the 1.4% required intervention rate.

Automated Metering and Spacing has just a small effect on the average IAT (77s vs. 81s) because the M&S buffer is almost equal to the manual buffer (26s vs. 30s). The major advantage of M&S comes from tightening up the distribution around that average (Figure 5-1). There are fewer actual IATs below 51 seconds (2 nmi at 140 kt), and therefore it is less likely, for a given mean ROC value, that an actual ROC would be greater than IAT and interventions would be required. We have chosen to keep the intervention rate constant and allow the mean ROC to increase instead.

The significance of these results is that 47s and 50s mean ROCs are not greatly different from the observed values at major airports today. Minimum separations of 2.0 nmi could be used without increasing intervention rates above present values, with an automated Metering and Spacing system and only minor improvements in average runway occupancy times.

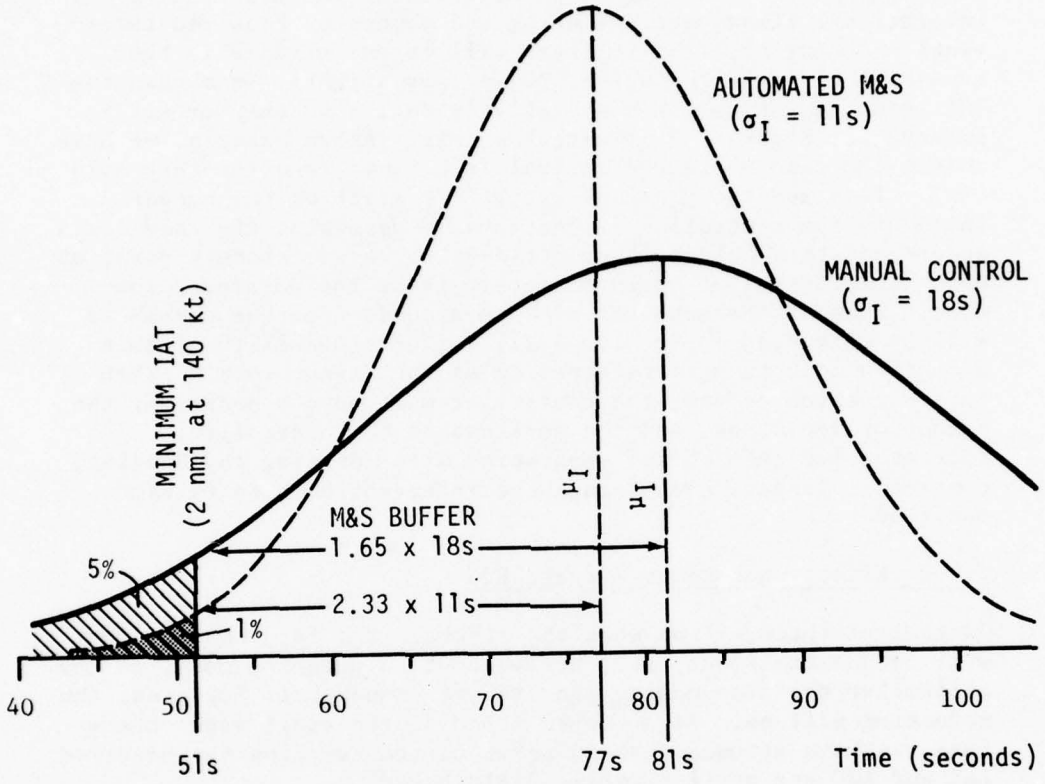


FIGURE 5-1
EFFECT OF M&S ON IAT DISTRIBUTION

5.4 Event Rates

5.4.1 Definition

A consequence of reducing σ_I and tightening the distribution of interarrival times, while keeping the number of required interventions constant, is that there will be an increase in the number of aircraft for which ROC is only slightly less than the IAT, and the controller must actively decide whether or not to intervene. Figure 5-2 illustrates this. As an example, we have chosen the case where the arrival is 0.5 nmi from the threshold (IAT - 13s) and the previous arrival is still on the runway. (Although the controller is continually assessing the need for a go-around, this half-mile point seems to be the closest point at which the controller would prefer to issue the go-around command. Some of the problems with go-arounds from the threshold will be discussed in Section 6.2.1.) The probability of this situation occurring is referred to as the "event rate." When this situation occurs, the controller must make a decision; the number of decisions, and the workload on the controller, increases for the 2.0 nmi separation with Metering and Spacing, compared to today, even though the intervention rate is kept constant.

5.4.2 Effect on Maximum Average ROC

Controller intervention when the aircraft are far from the runway will reduce the event rate, but without an accurate model of the controller decision-making process, we cannot tell how great the reduction will be. As an upper bound on the event rate, therefore, we have assumed that no previous intervention has occurred; IAT and ROC are still normally distributed.

The "event rate" can then be calculated in a manner similar to the intervention rate. We are interested in the probability that (IAT - ROC < 13s), for the situation described, and therefore

$$z_E = \left| \frac{x - \mu}{\sigma} \right| = \left| \frac{13s - .(\mu_I - \mu_R)}{\sqrt{\sigma_I^2 + \sigma_R^2}} \right|$$

$$z_E = \frac{\mu_I - \mu_R - 13s}{\sqrt{\sigma_I^2 + \sigma_R^2}}$$

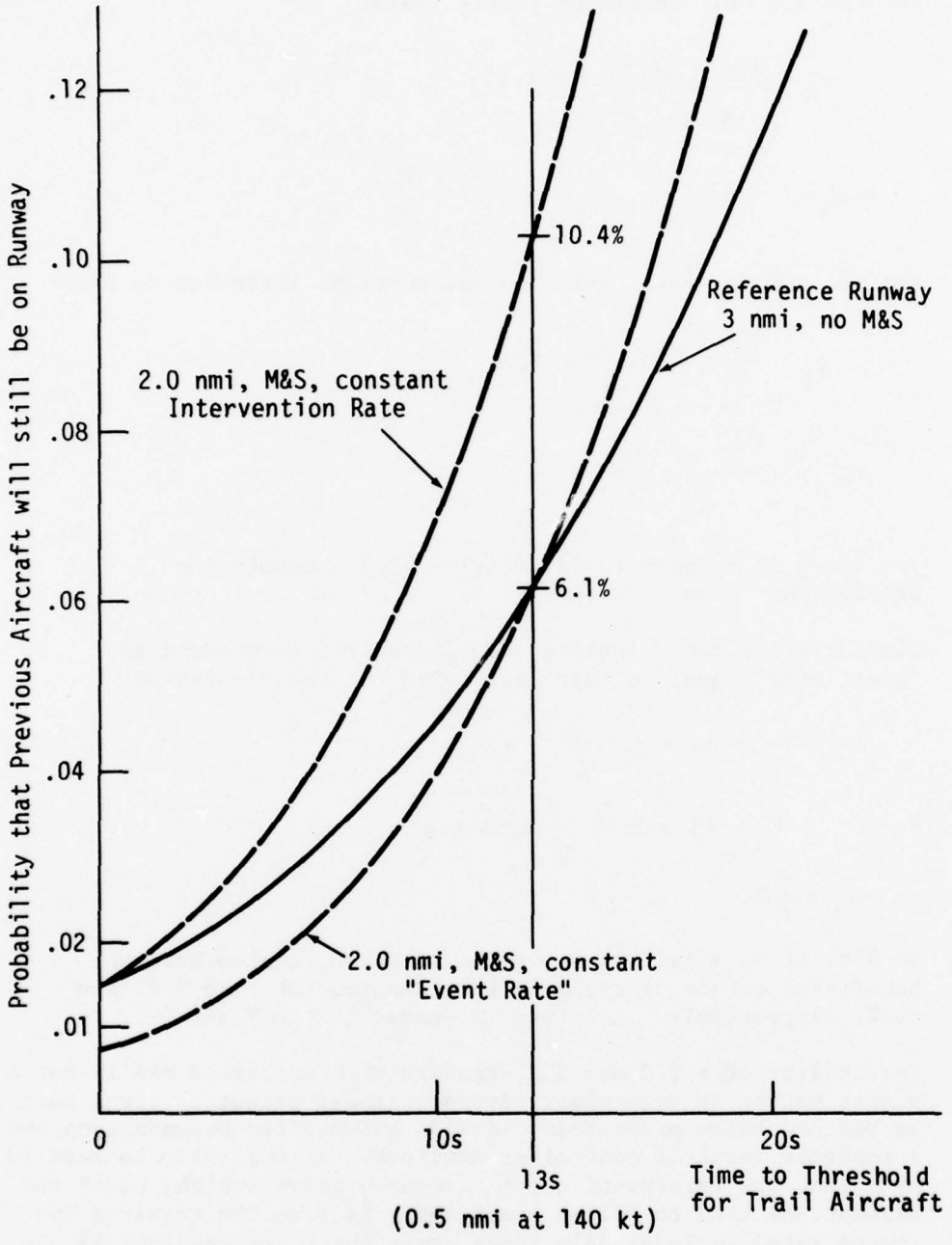


FIGURE 5-2
EFFECT OF M&S ON "EVENT RATE"

For the 3.0 nmi "reference runway" case:

$$z_E = \frac{107 - 63 - 13}{\sqrt{18^2 + 8.4^2}} = 1.55$$

$$\phi(z_E) = 6.1\%$$

For the 2.0 nmi case, with M&S and constant intervention rate:

$$z_E = \frac{77 - 47 - 13}{\sqrt{11^2 + 8.4^2}} = 1.26$$

$$\phi(z_E) = 10.4\%$$

or, if σ_R is reduced to 6s, $\phi(z_E) = 12.3\%$, double the present-day "event rate."

Similarly, we can calculate the μ_R required to produce an "event rate" equal to that calculated for today's system.

$$\mu_R = \mu_I - 13 - z_E \sqrt{\sigma_I^2 + \sigma_R^2}$$

$$= 77 - 13 - 1.55 \sqrt{11^2 + 8.4^2}$$

$$\mu_R = 43s$$

or 45s, if $\sigma_R = 6s$. These values of μ_R would also have the beneficial effect of reducing intervention rates to 0.7% and 0.5%, respectively. All this is summarized in Table 5-1.

Feasibility of a 2.0 nmi IFR standard with automated M&S is not a simple matter to determine. Average runway occupancy times must be reduced below present-day levels, but how far depends upon the acceptable level of controller workload. It must also be kept in mind that the intervention rate computed above (which, under the assumptions used to define event rate, is also the required go-around rate) includes only those cases which are required by regulation, and not those unnecessary interventions (i.e., go-arounds, in this case) which occurred because the controller

TABLE 5-1

COMPARISONS OF INTERVENTION RATES AND EVENT RATES

	3.0 nmi (σ_I = 18s 5% IAT buffer)	2.0 nmi w/M&S (σ_I = 11s, 1% IAT buffer)	
		σ_R = 8.4s	σ_R = 6.0s
CONSTANT INTERVENTION RATE			
μ_R	63s	47s	50s
intervention rate	1.4%	1.4%	1.4%
event rate	6.1%	10.4%	12.3%
CONSTANT EVENT RATE			
μ_R	63s	43s	45s
intervention rate	1.4%	0.7%	0.5%
event rate	6.1%	6.1%	6.1%

was overly cautious or just made the wrong decision at the half-mile point. As the "event rate" increases, and the number of controller decisions increases, the number of such unnecessary go-arounds is also bound to increase. The value of μ_R required to produce only an acceptable overall rate of go-arounds, both necessary and unnecessary, will be somewhere between the two values for constant intervention rate and constant event rate.

5.5 The Reference Runway Revisited

The idea of the "reference runway," it will be recalled, was to define a relation between average ROC and the minimum separation standard. In Sections 5.1 and 5.2, an average ROC of 37s or less, or 41s or less with a 6s σ_R, were determined to be required by a 2.0 nmi minimum. These values allowed a 5% buffer (1.65 σ_R) between the mean ROC and the minimum IAT of 51s (2.0 nmi at 140 kt).

Automated Metering and Spacing does not affect the mean ROCs required by the reference runway concept, since $_I$ and IAT buffer size are not considered. The mean ROCs derived above to keep event rates constant with Metering and Spacing, 43s and 45s, correspond to ROC buffers of 14% and 12%, respectively. In other words, if all arrivals were spaced exactly at the minimum of 2.0 nmi, 14% and 12% of the actual ROCs could be expected to be greater than the minimum IAT of 51s. Greater reliance would thus have to be placed on the IAT buffer to keep actual IATs above actual ROCs and avoid an unacceptable go-around rate. A decision on whether this is desirable will be required before M&S can be relied upon to make 2.0 nmi minimum IFR separations feasible.

5.6 Conclusion

Without other changes to the ATC system, a 2.0 nmi minimum separation would require an average runway occupancy time no greater than 37s-39s. Implementation of an automated Metering and Spacing system would allow operations with average ROCs as large as 47s-50s, without causing the required intervention rate to rise above levels assumed to be acceptable today.

By the standard of event rate, however, the controller's workload would increase unless mean ROCs were slightly lower, in the vicinity of 43s-45s. These ROC levels would also greatly decrease the intervention rates.

6. OTHER POSSIBLE REQUIREMENTS FOR SEPARATION REDUCTION

In the preceding analysis, it was shown that reduced IFR separations to 2.5 nmi and 2.0 nmi were possible if the improvements identified therein were realized. Those improvements would allow operations with acceptable levels of controller intervention and workload (according to certain measures). Nevertheless, there may be a natural desire on the part of the pilot and/or controller for some additional improvements that would increase their confidence in operating at the reduced spacing. Some possibilities are discussed below.

6.1 Communications Delay

6.1.1 Statement of Problem

During peak traffic periods presently, it may seem that the ATC frequencies are never quiet. Control instructions are being sent from the tower to the pilots, with acknowledgements and requests being returned. If separation standards are reduced, two possible effects on communications are foreseen: first, the loading on the communications channels would increase, and secondly, there would possibly be a significant delay in delivering the go-around command.

The additional channel loading caused by additional aircraft in the terminal area is not expected to be a serious problem. The 2.0 nmi IFR standard does, after all, approximate the visual separations currently used at many airports. The controllers at Washington National Airport to whom we spoke consistently made this comparison, and were consequently confident that a 2.0 nmi IFR standard would not cause them excessive work.

The second possible problem, however, is not quite as simple to resolve. Several techniques were discussed in Chapter 5 for implementing a 2.0 nmi standard, and these would give varying amounts of buffer time to the controller -- from the 44 second difference between mean IAT and mean ROC which is in effect today, to 27 seconds in one possible case. With potentially less buffer time and a tighter separation distribution, causing perhaps more aircraft to come close to needing to go-around, reliable communications become even more important.

The ability of the controller to immediately transmit the go-around command when necessary may be more important for user

acceptance of reduced separations than for operational or technical reasons. Thus, the full impact may not be known until reduced separations are proposed or implemented. Nevertheless, we can attempt to scope the severity of the problem and suggest some possible approaches.

6.1.2 Field Data

Appendix F fully describes the data which has been acquired on local controller voice channel utilization. The following summary contains some of the more important information.

For this basic analysis, two one-hour recordings of communications on the local control frequency (119.1 MHz) were obtained. The time period chosen represented peak traffic in definite VFR or IFR conditions at Washington National Airport. The lengths and type of radio messages were then tabulated and analyzed.

In VMC, the controller was on the frequency 27.5% of the hour: 12.1% for arrivals, 15.4% for departures. In IMC the controller was slightly busier, on the air for 30.9% of the hour, but with arrivals taking 18.4% and departures only 12.5%. In neither case is the controller near communication workload saturation, which is estimated to occur when communications occupy 60% of the time (Reference 14).

Such communication data could help calibrate a model of communication channel utilization, which could then be used to estimate future channel loading with reduced separation. Real time simulation will also be required to fully gauge the impact of separation reduction on channel loading, controller workload, and message deliverability.

In these tapes, the pilot was observed to be using the communications frequency only 12.1% in VMC and 11.9% in IMC. During the remainder of the time the frequency is either vacant or the controller is using it and can easily interrupt himself to deliver the go-around command. The controller cannot interrupt the pilot during a transmission, since two simultaneous transmissions would produce interference rendering them both unintelligible, but most of the pilot messages are short and, therefore, would not severely delay the go-around message. In IMC, in fact, almost 40% of the pilot messages recorded were less than 2.0 seconds long; 95% were less than 3.3 seconds, and only 1% were longer than 6.5 seconds.

Although long transmissions can occur, the expected waiting time for any controller transmission is less than a second. The probability of a long transmission occurring just in time to affect a go-around which is also rare, is exceedingly small.

6.1.3 Communication Alternatives

If, regardless of the small probability that the channel will be blocked for an significant period when a go-around is required, it is decided that the situation is unacceptable, there are many alternatives for improving or alleviating these conditions. The simplest would be to reemphasize proper communication discipline among pilots and request them to limit their transmissions in a busy terminal area. This would not, however, avoid such mechanical problems as the stuck mike button or defective transmitting relay. In these cases, an alternative mode of communication would be required.

A different radio frequency could be used. Using separate frequencies for arrivals and departures would reduce the probability of a long transmission since there would be fewer transmissions per channel. Nevertheless, a blocked channel could still occur, and the separate frequency would have no effect other than to complicate everyday operations. Alternatively, the go-around command could be broadcast on the emergency frequency, 121.5 MHz, if pilots would monitor this frequency during the approach (or if aviation radios were designed to always receive this frequency in addition to the channel selected). Or the localizer frequency which currently carries the ILS identifier signal could be used -- but again the pilot would have to monitor this frequency more thoroughly than is presently the case. If a different frequency were used, the controller would need an immediate and positive switch to the new frequency.

In the 1980s, digital data links will come into use which might help this communications problem. Both MLS and DABS have associated data link message capabilities. Neither one has so far been designed with the go-around message in mind, and they share some other drawbacks as well: a rapid method to input the message and the aircraft ID would have to be developed and implemented, and a significant fraction of the traffic would have to have the necessary receiving equipment, for data link to be practical for this application.

DABS data link does have the potential to drastically reduce communications channel loading by handling all routine ATC message and pilot acknowledgements. Voice radio could then be

reserved for non-routine messages; but since these can be exceptionally long and might block the go-around message, the problem would be relatively unaffected.

Lastly, some non-radio means could be used to signal a go-around. The simplest of these could be a circuit which, when activated by a controller switch, would flash the VASI lights, threshold lights, or some other part of the approach light system which is normally steady burning. To be effective, the signal would have to be visible soon enough for a missed approach to be performed, and not be confused with a normally-flashing part of the system.

6.2 Cockpit Devices

An alternative to communication from the controller on the need for a go-around would be to provide sufficient information to the pilot for him to decide for himself. Whether or not communications blockage ever occurred, this cockpit display of separation information could possibly improve the pilot's willingness to accept the reduced standards.

6.2.1 Types of Cockpit Display

The simplest type of cockpit display would be a red/green light on the panel to indicate whether or not a go-around was required. This could be just a communications backup regulated by the local controller, but it is extremely doubtful that the airlines would install such a device if it were only used during the rare blocked-communications situation.

Such a device would be more attractive if it provided independent information to the pilot on the need for a go-around, such as the presence (red light) or absence (green light) of other aircraft on the runway. But it would be difficult to establish practical procedures to use such information. Should a go-around be initiated at the half-mile point if the light is still red? The probability analysis showed that this might happen 6% of the time today, but in three quarters of the cases the preceding aircraft would have exited by the time the arrival reaches the threshold.

Should the pilot wait until he is at the threshold before reacting to the red light? This would eliminate the unnecessary go-arounds, but threshold go-arounds raise other serious questions of safety and pilot acceptance. Clearance over the aircraft on the runway is not assured because the go-around would

probably lose altitude and even touch the runway briefly (Reference 15) before the engines spooled up to climb thrust (6-8 seconds). Although pilots are trained in threshold go-arounds as part of their commercial license requirements, such maneuvers are rarely needed currently. Threshold go-arounds seem to be associated in the pilot's mind with Category IIIA approaches (which may be defined to include a 50 foot decision height -- for practical purposes, over the threshold), and Category IIIA operations require special training and equipment which pilots may assume is necessary for the threshold go-around.

Such an automatic red/green light suffers from a lack of anticipation of the actions of the aircraft on the runway. A more complex display would be required to give the pilot adequate information to anticipate the go-around need. Such information could be incorporated in either of two systems currently under development: Cockpit Display of Traffic Information (CDTI) and the Head Up Display (HUD).

The CDTI was originally intended to pictorially display traffic information on an instrument panel mounted cathode ray tube. This traffic information could include the position of aircraft on the runway. The HUD projects approach and landing information (airspeed, angle of attack, runway location) on a combiner glass in such a way that the pilot sees this data while looking through the windshield. It might be possible to include a moving aircraft symbol on the synthetic runway image in the HUD.

Such information would be helpful, but it would still not be as useful as the judgement of a good controller. A journeyman controller at a field has experience with aircraft using a particular runway and should be able to recognize unusual behavior which might lead to extra-long occupancy times. He is usually in a better location to visually judge the speed of the aircraft on the runway than the pilot on final approach. The tower controller knows the airline and aircraft type, and possibly the individual pilot, and should be familiar with the typical exiting behavior. And he will be involved in many, many more landings each day than the pilot of even a short-haul commuter airline.

Although in most cases the controller should be better able to make the go-around decision, a possible exception would occur if visibility conditions were so poor that the controller could not see the runway. But in this case, the same sensors required to obtain information for CDTI or HUD could supply this information to a display in the tower cab for the controller to use.

The information could still be provided to the pilots, for their assurance and as a safety backup, but a display for the controller has the advantage of utilizing the controller's experience with operations at that airport. Also, one display in the cab could thus serve (indirectly) all aircraft using the airport, thereby avoiding the problems of basing procedures on equipment which is not in use by all aircraft. Providing this information to the controller should satisy the requirements described in previous chapters for adequate controller surveillance of the approach path and runway.

Cockpit displays of go-around information might have a place as pilot confidence builders, but they do not seem to be operational necessities. The benefits of providing go-around information to the pilot are likely to be increased willingness to accept reduced separations and additional safety in case of ATC failure, with possibly low incremental cost if the necessary cockpit display is utilized for other functions as well. Possible penalties (such as increased pilot/controller workload, decreased efficiency, or more pilot-initiated go-arounds due to misinterpretation of the display) can be minimized by operational procedures which emphasize the relative strengths of the air and ground systems. The benefits and penalties need to be quantified through simulations and tests under real-life conditions.

6.2.2 "Electronic VFR"

The opinion has been expressed that cockpit displays like CDTI are essential for separation standard reduction because they can produce a sort of "electronic VFR" in IFR conditions. In VFR today pilots can apply visual separation to the aircraft ahead of them; actual separations are closer than in IFR, and the observed data shows effective "minimums" which are close to 2.0 nmi (Reference 11). The idea is that CDTI, by allowing the pilot to establish his own spacings even in IFR conditions, would result in the same spacings as exist in VFR today.

It is not clear, however, whether true "electronic VFR" on final approach and landing is possible even with sophisticated cockpit displays. In addition to information on other airborne aircraft for spacing purposes, the VFR pilot also has visual data on

- -- runway orientation and distance, and aircraft altitude, for the approach and landing
- -- the position and probable actions of aircraft on the runway, for the go-around decision

-- obstructions in and near the approach area and, if a go-around occurs, in the missed approach area

-- runway environment, such as distance to the end, exit location and angle, and traffic on adjacent taxiways, for planning the rollout.

Some of this data can be provided by a plan-view display of navigation and traffic information similar to some CDTI concepts. Other data might be better presented on a forward-view display which approximates the pilot's view through the windshield. Examples would include HUD and the Electronic Altitude Director Indicator (EADI). The EADI, as currently being tested at NASA Langley as part of the Terminal Configured Vehicle (TCV) program (Reference 16), can combine flight instrumentation and computer-generated symbols with the picture from a forward-looking low-light level television camera, presented on a single head-down display.

The challenge for researchers is to design a practical cockpit display which provides the right information in the right format for pilot use, with adequate update rates and accuracy. There are some doubts that providing all the data needed for "electronic VFR" is technically possible (Reference 17). Operational feasibility must also be established. Simulation exercises are needed to determine whether proposed displays are adequate for pilot use, whether they can be used effectively and efficiently, and what effect they would have on actual separations and pilot/controller workload.

6.2.3 Effect on Maximum Average ROC

It has also been claimed that a cockpit display of navigation information which included a "target position" for the aircraft could greatly reduce the standard deviation of interarrival spacing. Reference 18 quotes a 3-second value of σ_I for a combination of CDTI and 4D RNAV, where the CDTI display included both current and desired position information. It is not clear, however, how much of this benefit is due to the CDTI navigation display and how much to the 4D RNAV, nor how much could be realized in actual practice.

Reducing σ_I to 3s would greatly benefit capacity. However, the effect which this would have on intervention rates is not necessarily as beneficial as might be expected, because of the

effects of extreme tightening of the IAT distribution (Figure 6-1). The maximum average ROC compatible with 2.0 nmi minimums and a 3s σ_I would be:

$$\mu_R = \mu_I - z_{IN}\sqrt{\sigma_I^2 + \sigma_R^2}$$

$$= \left[51 + (2.33 \times 3)\right] - 2.19\sqrt{3^2 + 6^2}$$

$$= 44s$$

This is more demanding than the requirements for Metering and Spacing, even though the most favorable assumptions were chosen (i.e., a 1% buffer and 6s σ_R).

If we choose to keep the event rate constant rather than the intervention rate, the result is even more restrictive.

$$\mu_R = \mu_I - 13 - z_E\sqrt{\sigma_I^2 + \sigma_R^2}$$

$$= 58 - 13 - 1.55\sqrt{3^2 + 6^2}$$

$$= 35s$$

If the reduction in σ_I is not coupled with an increase in IAT buffer, most reliance for go-around avoidance would be placed on the average ROC rather than on the IAT buffer, as in other cases. This leads to extremely restrictive requirements on μ_R in order to achieve a 2.0 nmi minimum.

However, it is not the minimum separation but the mean IAT which directly affects capacity which, after all, is what we want to improve. Capacity, defined as maximum throughput, can be expressed

$$CAP = 3600s/\mu_I$$

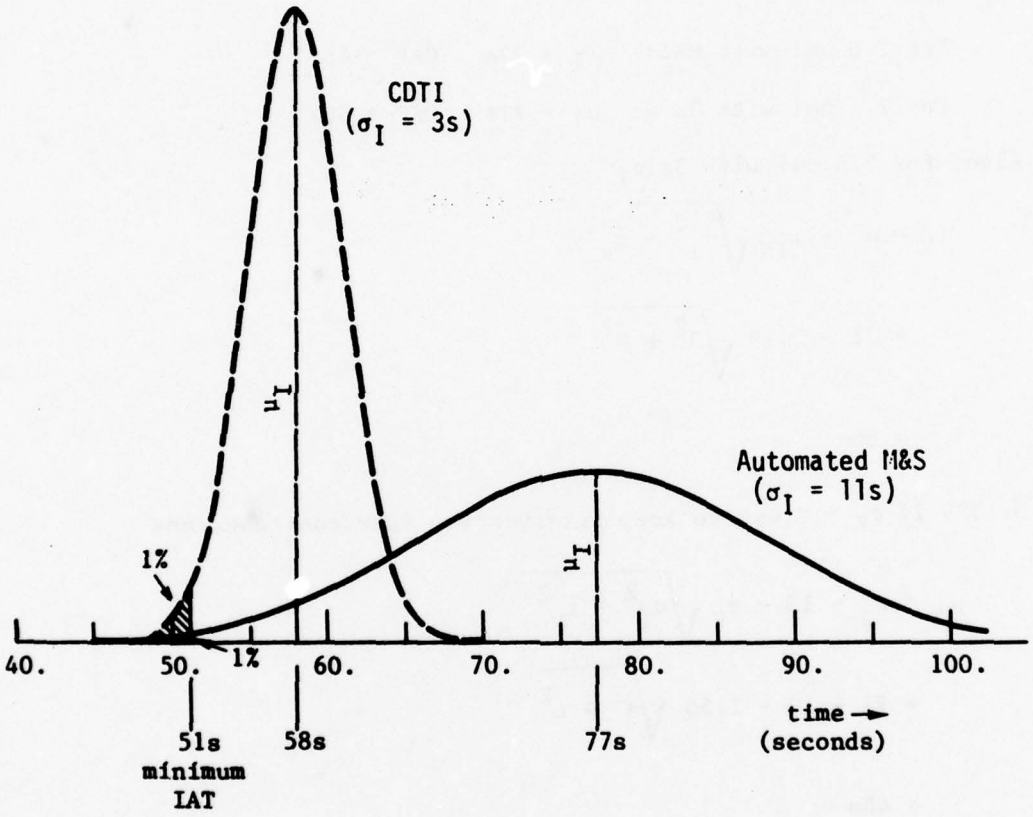


FIGURE 6-1
POSSIBLE EFFECT OF CDTI ON IAT DISTRIBUTION

In the simplified examples in this analysis, mean IAT is not affected by ROCs, and all aircraft have the same approach speed, so that

$$\mu_I = \frac{3600 * S}{V} + z_I \sigma_I$$

The reduction in σ_I due to a cockpit display can have a big impact on capacity.

For 2.0 nmi with M&S: μ_I = 77s CAP = 46.7

For 2.5 nmi with 3s $_I$: μ_I = 71s CAP = 50.5

Also, for 2.5 nmi with 3s σ_I

$$\mu_R = \mu_I - z_{IN} \sqrt{\sigma_I^2 + \sigma_R^2}$$

$$= 71 - 2.19 \sqrt{3^2 + 6^2}$$

$$= 56s$$

or 52s if σ_R = 8.4s, to keep intervention rate constant, and

$$\mu_R = \mu_I - 13 - z_E \sqrt{\sigma_I^2 + \sigma_R^2}$$

$$= 71 - 13 - 1.55 \sqrt{3^2 + 6^2}$$

$$= 48s$$

or 45s if σ_R = 8.4s, to keep event rates constant. Table 6-1 compares these results with those for 2.0 nmi with M&S.

TABLE 6-1

COMPARISON OF CDTI AND M&S

	σ_R	μ_R CONSTANT INTERVENTION RATE	μ_R CONSTANT EVENT RATE	CAP.
2.0 nmi w/M&S	8.4s	47s	43s	46.7
	6s	50	45	
2.5 nmi w/CDTI	8.4s	52	45	50.5
	6s	56	48	

These results can be summarized as following: if σ_I can be reduced to 3s, by CDTI or any other means, then a substantial capacity benefit will result with only a half-mile reduction in the minimum standard (for which vortex safety will be easier to prove than for a full mile reduction) and a slight improvement in mean runway occupancy times (not to keep go-around rates down but to limit the number of controller go-around decisions).

The principal problems with relying on a 3s σ_I to reduce separation standards still remain, however. The first is that achievement of such levels of σ_I has not yet been demonstrated in a realistic operational environment. The second is that, whether this σ_I is achievable by cockpit display alone or by cockpit display plus some other system like 4D RNAV, this σ_I would be available only for those aircraft with proper equipment on board. Only a fraction of all aircraft will be so equipped, at least at first and possibly, due to equipment costs, for much longer. Will it be operationally feasible or effective to reduce separations for only the faction of properly equipped aircraft?

Further research on the application of cockpit displays is required to resolve these questions.

6.3 Implementation -- Airport-Specific or Universal

An onboard-equipment requirement for reduced IFR separations is one example of a situation in which the reduced separations would apply to only one class of aircraft: in this case, those which have the appropriate cockpit displays. In fact, there are few cases in which it would be possible, or even desirable, to reduce separations for all aircraft at all airports. Implementation is more likely to be on an airport-by-airport basis, rather than universally, despite the advantages of uniform IFR procedures and regulations.

Reduced separations will require certain levels of runway performance and perhaps some special equipment as a condition of implementation. If these requirements are met by all airports, then the reduced separations can apply to all airports. It may be possible (although unlikely) to allow 2.5 nmi separations on a universal basis, since the required average ROC is not greatly different from some current-day levels. There would be exceptions, runways like ORD 22R where such separations cannot be run and small airports where they are not needed.

More likely for 2.5 nmi, and almost certainly for 2.0 nmi separations, each runway and airport will have to be approved individually. Certain criteria, such as an average ROC or particular pieces of ATC equipment, will be required. Although the present analysis assumed no wake vortex effects, WVAS (Wake Vortex Avoidance System) will almost surely be required even for the 2.5 nmi standard, and WVAS will not be installed at all airports.

The confusion potential of having different separation standards at different runways could be lessened somewhat by limiting reduced separations only to a given category of airports, such as within Group I TCAs (Terminal Control Areas), where special procedures are already in effect. This would be most effective if the category already existed for some other purpose (like TCAs), and if all airports within the category were eligible. However, the actual implementation of reduced IFR separations at any airport should depend upon the conditions at that specific airport; it should not be automatic for all airports in a given category.

7. REDUCED SEPARATIONS AND DEPENDENT PARALLEL RUNWAYS

The analysis of reduced separation standards has so far concentrated on operations to a single runway, but this is not necessarily the only feasible mode of operation. As mentioned in Chapter 2, some alternative modes utilizing close-spaced, dependent runways offer the possibility of avoiding runway occupancy time as an operational constraint. This chapter will discuss some of the possibilities and point out some of the areas where further research is required.

Dependent parallels are separated by 700 to 2500 feet and can therefore be operated independently in VFR, but simultaneous arrivals and departures are not possible in IFR. Dependent parallels could be fed by either a single arrival stream or by parallel streams.

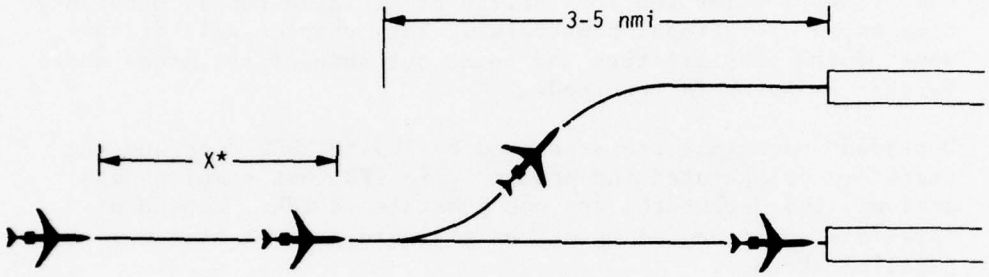
A single stream of arrivals at reduced spacings would require that every other aircraft sidestep to the secondary runway at about 3-5 nmi from the threshold. This technique is restricted by the limited maneuverability of large aircraft and by relatively high weather minima, greater than for an ILS approach but generally lower than the minima for a circling approach.

With parallel streams, the aircraft are positioned alternately on the two approach paths. Separation standards are applied either on the diagnonal or perpendicularly along the approach path, between each aircraft and the one ahead of it on the approach to the other runway. In this manner, the interarrival time between arrivals to the same runway would be large enough that runway occupancy times would not restrict operations. These two methods of utilizing dependent parallel runways are illustrated in Figure 7-1.

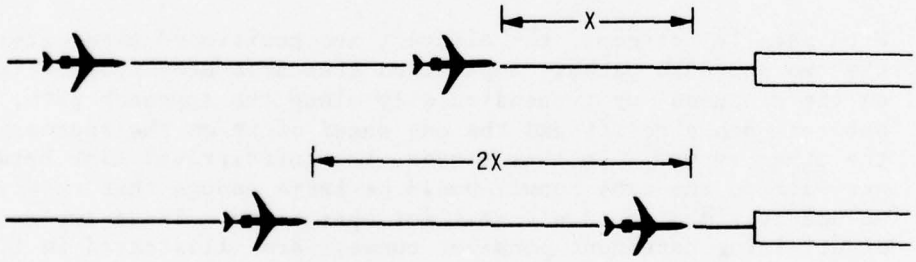
7.1 Operational Feasibility

The limitations on the sidestep approach severely restrict its usefulness. The limitations on staggered approaches are not as well defined, but seem to center on the controller's ability to maintain this procedure for any length of time.

A preliminary analysis of the operational feasibility of staggered approaches is described in Appendix G. The analysis was greatly simplified, assuming just a single aircraft type and fixed values for interarrival time, runway occupancy time, taxi



A. SIDESTEP APPROACH



B. STAGGERED APPROACHES

*X = average separation

FIGURE 7-1
SIDESTEP AND STAGGERED APPROACHES

times, etc. It was intended as just a first look at the problems of sequencing arrivals and departures on the runway when staggered approaches are being conducted.

The analysis revealed no severe operational problems. Arrivals on the outer runway were able to cross the inner without disrupting the stream of arrivals to that runway, although some delay was incurred in holding short of the inner runway until the inboard arrival rolled past. Adequate natural gaps seemed to exist as well for departures to cross to the outer runway. The ability to sequence a departure between each arrival pair depended upon the actual IAT; at the average IAT (minimum plus buffer) interleaved departures were possible at all separations, while at minimum IAT they were possible only on the outer runway at 2.5 nmi, and not at all at 2 nmi. It is an advantage of staggered approaches that an unusually short IAT or long ROC would only result in a briefly delayed departure rather than a more fuel-costly go-around.

These results are by no means conclusive, since they apply solely to an extremely restrictive, simplified set of assumptions. However, they are persuasive that the analysis of staggered approaches should continue. IATs, ROCs, taxi times and runway crossing times should be varied in a more realistic, dynamic manner. The effect of different centerline spacings and taxiway geometries should also be studied. Analytical models might be adequate for general results, but a dynamic simulation model would be useful for more detailed operational studies.

Controller workload is another area where more information is required. With staggered approaches, the tower controller would have to continually monitor operations on the runways, deciding when to allow aircraft to cross the inner runway, whether a departure could be released, and so on. Reference 19 concludes that mixed operations on dependent runways are "not realistic" in IFR conditions because of the lack of visual information available to the tower. The beneficial effect on workload of a system such as TAGS, which would provide the controller with a high-resolution radar image of the airport surface with alphanumeric ID tags for each aircraft, should therefore be evaluated.

7.2 Technical Feasibility

The use of staggered arrivals in IFR conditions implies that ILS guidance is available to both runways. Questions then arise about possible ILS interference, marker beacon interference, etc.

Some practical experience with close parallel ILS operation has been gained at San Francisco International Airport which has two pairs of close parallels (750' spacing). According to Mr. Lou Martin, the Deputy Tower Chief at SFO, the ILSs are always in operation. There have never been any reports of interference between the glide path signals (which are at different frequencies), although the middle markers for the close parallels, which use the same frequency, do interfere with each other; consequently, only one middle marker is operational at a time. This may present one technical limitation on staggered arrival operations, but fortunately, the middle marker is not required for CAT I approaches.

At SFO a single outer marker is used for both 28R and 28L. According to Reference 20, the maximum allowable outer marker displacement from the runway centerline is 800 feet. At centerline separations above 1600 feet, therefore, two outer markers would be required, and if they interfered with each other like the middle markers at SFO do, then the maximum centerline separation for staggered approaches may also be technically limited.

Based on the experience at SFO, it would seem that the use of dual ILSs on dependent parallels is technically feasible. Radar beacon garbling, another potential problem, can also be discounted based on actual operations in VFR conditions at SFO (see Section 2.5)

7.3 Unresolved Questions

There are other potential problem areas which are recognized but which have not yet been addressed. For example,

- the effects of wake vortices must be considered, although this aspect is outside the scope of the present phase of this project;
- separation and control of the arrivals in the air, before they are established on final approach, must be addressed, particularly the transition to final approach;
- special equipment and procedures may be needed to guarantee that aircraft are landing on the proper runway. Prudent selection of ILS frequencies would help, of course, but a final approach monitor may also

be required. In this case, the capabilities and limitations of existing radars (target position error, target slash size, beacon garbling) may limit the airborne separations and/or the centerline spacings at which staggered approaches are feasible.

The use of dependent parallel runways for staggered arrivals is one possible means to implement reduced separations. The main benefit of this procedure is that it avoids the need for reduced runway occupancy times, a principal requirement for reduced separations between arrivals to a single runway. For this reason, it is recommened that such staggered arrivals should be investigated further with the goal of implementation in the near future.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Apart from wake vortex considerations, the need to keep go-around rates to acceptable levels is the most significant constraint to separation standard reduction. A 2.5 nmi IFR separation for air carrier aircraft appears feasible if average ROC can be reduced to 50 seconds; a 2.0 nmi standard would require a 37s average ROC, if no other changes in the ATC system are considered. An automated Metering and Spacing system and a reduced standard deviation of ROC would raise the maximum allowable average ROC to 50s for a 2.0 nmi standard. Considerations of controller workload would require an average ROC no greater than 45s, however. This level of occupancy time should be achievable at most high-density hub airports through pilot motivation and the use of properly located exits. New exits should utilize current standard designs for high-speed and conventional exits; existing exits should be modified to the standard design.

At reduced separation standards, adequate controller surveillance from the middle marker to and including the runway and taxiways, either visually or on radar, is required. In addition, experience at the closer separations may establish a requirement for a separate communications channel or independent cockpit surveillance during the approach. Although the technical need for these items is still uncertain, they may be necessary for user acceptance of the reduced separation standards.

The specific operational and technical requirements for reduced IFR separation standards will preclude universal implementation of the reductions. Rather, implementation should be based on the characteristics of the individual airports.

Finally, staggered approaches to close-spaced, dependent parallel runways could provide a more readily implementable method of operating at reduced separations. However, some technical and operational questions exist here as well.

8.2 Recommended Actions

This analysis has resulted in a set of requirements for separation standard reduction. Before reduction can be implemented, additional research and analysis effort is required to verify the assumptions herein, to extend the analysis of reduced separations, and to develop methods and procedures whereby the identified requirements can be fulfilled. Coordinated actions by the FAA, NASA, and the aviation community will be required.

8.2.1 Steps Required for the Achievement of a 2.5 nmi Minimum Standard

The following steps are seen as necessary before a 2.5 nmi standard can be implemented:

1. Resolution of the wake vortex safety question for 2.5 nmi airborne spacing by modifications to the Vortex Advisory System (VAS) or by other means.

2. Validation of the achievability of average runway occupancy times in IMC in the range of:

   -- 50s for implementation in the current manual control environment.

   -- 58-62s for implementation in the Metering and Spacing environment.

3. Implementation as required of operational means to reduce runway occupancy times to the necessary levels (i.e., construction and use of high speed exits, runway and exit grooving, development of procedures by airlines to encourage expedited exiting).

4. Validation of related numerical assumptions and/or calculations of:

   -- Manual control and Metering and Spacing system interarrival time standard deviations.

   -- Controller intervention rates and go-around rates in IMC.

   -- Local control radio channel usage.

5. Development of appropriate weather minima and/or electronic aids to local controller visibility for the region from the middle marker to threshold, to assure positive awareness of aircraft position on final approach when reduced separations are in effect.

6. Development of positive, fail-safe local control procedures for observation of the final approach spacing process, and for the issuance of intervention action commands (i.e., expediting exiting or go-around) for use both in reduced separation situations and in ordinary operations.

7. Evaluation of the use of staggered, dependent approaches on close-spaced parallel runways as a means for overcoming limitations to reduced separation operations that may be imposed by runway occupancy problems.

8. Upon substantial completion of the above steps, development of a complete safety analysis and flight test validation procedure on the proposed reduction to 2.5 nmi final approach spacing for presentation to, and evaluation by, the FAA operating services and the airspace users. This analysis would form the basis for discussion and support of any proposed changes to FAA orders or procedures, or other rulemaking actions that would be required in the reduction.

8.2.2 Steps Required for the Achievement of a 2 nmi Minimum Standard

The steps listed above for 2.5 nmi apply as well to 2 nmi. The 2 nmi spacing would be expected to be implemented on single runways only with improved delivery accuracy. With the automated Metering and Spacing system described herein, average runway occupancy times in IMC in the range of 45 to 50s would be required.

A 2 nmi IFR standard would also require an investigation, through simulation and/or flight tests, of human performance in the Metering and Spacing/reduced separation environment. This would include such areas as pilot response to controller communications, pilot/controller workload, and controller judgment of intervention needs. Such an investigation could lead to a detailed requirement for the development of an independent communications channel for go-around commands (i.e., voice over ILS frequency, DABS data link, or other means), or the possible requirement for cockpit displays for independent verification of a clear runway.

In addition, the use of staggered approaches to dual lane runway with dual ILS (Step 7) should be considered as an appropriate means to achieve 2 nmi within the current manual control environment (that is, for possible reductions without recourse to automated Metering and Spacing) without severe reductions in runway occupancy times.

8.2.3 Recommended Engineering and Development Actions

This analysis has indicated the feasibility of reduced separation operations and the steps to be taken to achieve these goals. There are a number of specific FAA Engineering and Development

actions that are needed in order to prepare for separations below the present 3 nmi minimum. Many of these actions apply equally well to the achievement of 2.5 nmi and 2 nmi standards as outlined above.

In order to verify assumptions made in this analysis the following actions should be taken:

1. An investigation should be undertaken of the wake vortex problems and vortex system requirements associated with separations below 3 nmi. This should include a reevaluation of the Vortex Advisory System data base for 2.5 and 2 nmi minimum spacings, and the development of means to improve the effectiveness of the vortex advisory system (i.e., the inclusion in that system of additional meterological data that better identifies conditions of rapid vortex decay). Procedures for transitioning from en route separations to lower terminal area spacings should be investigated. Evaluation should be made of the applications of advanced vortex systems, including vortex alleviation techniques, to the reduced separation environment. Both technical and operational requirements should be addressed. Once the parameters of the vortex advisory system and other vortex techniques are established for reduced separations, the vortex program should be directed towards the most cost- and safety-effective approach to achieving reduced separations. At this time the exact technical means for achieving these separations in a vortex environment cannot be identified.

2. Field surveys should be conducted to collect data on IMC runway occupancy times, local control channel communications usage, controller intervention rates and the rate of ATC-initiated go-arounds in IMC, to validate the assumptions and calculations of this analysis. The preparation of specifications for the collection of these data is being undertaken as a follow-on to the present studies. The data should then be related to the results of the present analysis, and a sensitivity analysis should be prepared.

3. The current interarrival spacing error, and the improvement to that error from automated Metering and Spacing systems, should be carefully determined within the Metering and Spacing development program of FAA.

In order to continue the analysis of reduced separation standards to the refinement necessary for justification to the FAA operating services and the user community, the following actions must be taken:

4. The human performance aspects of the go-around process, such as pilot landing expectations and response to go-around commands, as well as pilot/controller workload, and controller judgments of aircraft spacings and requirements for intervention, should be studied. This evaluation will require real time simulation and flight test activities that may best be performed as part of the current ATC human factors program being conducted by FAA. It is expected that this phase of the work will lead to improved positive control procedures for final approach, and will identify any specific requirements for specialized communications channels or cockpit displays.

5. A review should be conducted of current FAA programs to reduce runway occupancy times and to improve runway surface and braking conditions. The potential impact of these improvements on the runway occupancy times of specific runways at major airports that would be candidates for reduced separation operations should be estimated.

6. The analysis of the potential use of staggered dependent approaches to dual lane runways should be expanded and should include more realistic and variable parameters. This study must consider the following as yet unaddressed problems:

-- Wake vortex problems

-- Lateral, longitudinal, and vertical separation requirements and trade-offs

-- Manual or automated Metering and Spacing accuracy and procedural requirements

-- ILS and other navigational requirements

-- Potential advantages of staggered thresholds or use of Microwave Landing Systems

-- Requirements for controller surveillance of runways and approaches

-- Techniques for management of aircraft on runways and taxiways, including departures

-- Safety assurance techniques (i.e., runway identification, crossing control)

The initial phases of this activity are being undertaken as a follow-on to the present study.

In order to implement the insights gained from this analysis, the following actions should be taken:

7. Reduced separation requirements should be incorporated into plans for airport surface traffic control systems and other surveillance projects, cockpit display studies, and elsewhere. Improving threshold delivery accuracy through the use of cockpit displays should be investigated further.

8. Representatives of air carriers that operate large aircraft should be asked to develop a plan to improve pilot runway occupancy performance. This plan should consider two future regimes:

   -- The use of present equipment with revised procedures

   -- The use of improved equipment (i.e., automatic braking, ground speed indication through INS or other means)

9. Work should commence well in advance of possible reduced spacing implementation dates on the identification and evaluation of all factors that must be included in the reduced separations safety analysis. A first step of this activity should be to review for FAA operating services and pilot and operator user groups the methods, assumptions, and conclusions of the present study. Following this review, all participants should identify the elements to be required of the safety analysis, and the analytical and/or live test techniques that will be employed prior to implementation of reduced separations. It is essential that this latter action be conducted in parallel with the above activities in order that all factors of concern will have been identified and evaluated prior to any move to implementation of separations below 3 nmi.

The continuing research program recommended above will help establish the criteria for reduced separation standards at individual airports, thereby enabling a better appraisal of the feasibility of reduced standards. The results of the analyses to date in this area have revealed no insurmountable obstacles or hidden dangers; further investigation should delineate the best paths to implementation.

APPENDIX A

APPROACH CONTROL AT WASHINGTON NATIONAL AIRPORT

A.1 Background

During the months of May and June 1977 several visits were made to Washington National Airport (DCA) for the purpose of collecting information on the actual operation of the ATC system, particularly the interpretation of official rules in daily practice. To achieve this we observed the activity in the tower and the radar room, but most information was obtained by directly interviewing controllers and administrators. The following individuals were interviewed:

Harry Hubbard	Tower Chief
William Canty	Operations Officer
Anthony Spinoa	Operations Staff
Lee Moses	Training Officer
Frank Conway	Training Officer
Robert Goss	Controller
Rico Imundo	Controller
Gary Wolfe	Controller
Dale Young	Controller

The controllers were all journeymen, fully qualified at DCA, with as much as twenty-five years of experience.

Some of the following information was also obtained from written sources, such as the DCA Operations Manual (Reference 21) and the Controller's Handbook (Reference 5). We found that such sources provided a basis for actual procedures, but that the final interpretation was derived from on-the-job training.

Washington National was chosen as an information-gathering location for several reasons, in addition to being convenient to MITRE's Washington site. Its heavy traffic levels mean that operations are

frequently conducted at minimum separations. No heavy aircraft currently operate from National, so wake vortex is not a major consideration. On the negative side, National has only one main runway, so mixed operations (arrival-departure, rather than arrivals-only) are conducted more often than might be the case elsewhere. However, operations at minimum separations occur frequently enough at DCA that we obtained useful information on the procedures in such cases.

As a final reason for visiting National, the ATC personnel there have been visited and interviewed by MITRE personnel in the past and have always been most helpful and cooperative. This time was certainly no exception.

A.2 A Typical Arrival in VMC

To illustrate the operation of ATC at National Airport, we will follow a typical arrival in visual conditions. The flight is handed off by the Leesburg center to one of two arrival controllers located in the TRACON at National Airport, depending on whether the arrival is coming from the east or the west. The arrival controller will then hand off the aircraft to a final controller. There are also an east and west final controller. Not all facilities have a final controller position, but this is the procedure used at National to handle the traffic volumes there.

Aircraft being handled by the final controller are generally separated by about ten miles from each other. The two final approach streams are merged together in the vicinity of the outer marker, with resultant five mile separations. At this point the aircraft will be handed off to the local controller in the tower cab.

During VMC visual approaches are used as often as possible. The aircraft crew is then responsible for maintaining separations. One controller stated that most pilots are not accurate at maintaining separations visually; for this reason, radar separation is maintained until the aircraft turns onto the final approach. The procedure is generally to have arrivals fly their downwind leg about three miles laterally from the final path. When they are directly abeam the aircraft on final which they are to follow, the controller will authorize the turn to final and visual separation. The local controller will still monitor the separations; according to one controller, if spacing gets as close as two miles, the controller will verify that the arrival does have the preceding aircraft in sight, and will take action if separation drops to one mile. The trail aircraft will usually allow enough separation to avoid a go-around, however.

A landing clearance is given to the pilot by the local controller, fairly close to the runway during heavy traffic periods, but as far as two to five miles from the threshold during less busy times. The local controller will visually scan the runway to verify that it is or will be clear for the arrival. However, a landing clearance does not preclude a go-around, if needed.

In visual conditions, visual landmarks will be used by the controller as decision-making aids. The end of the approach light pier, for instance, one-half mile from the threshold, is a preferred position for issuing a go-around (see Section 3-2). Visual assessment of the aircraft on the runway is a continuous process, of course, but some landmarks are used here too. For example, if an aircraft landing on runway 36 at DCA rolls past both exits I and J (see Figure A-1), the usual exits, the controller knows that the plane will take about fifteen seconds to roll to and use the next exit, which is the runway end 1500 feet away.

Several buildings and other landmarks off the airport are used to estimate the required two-mile separation between an arrival and the preceding departure. The exact references used varied between controllers. Each controller devised his own or used the ones passed on to him during his training. The BRITE radar display in the tower is used as a backup and to give the controller information about upcoming gaps in the arrival stream.

A.3 Exceptions to Normal Procedures

Due to the inexact nature of the control process, an additional separation is usually applied between aircraft above the minimum required. If a visual separation is getting too tight, or if an arrival is closing the gap required to get out an interleaved departure, there are several steps that the controller can take to avoid violating the required minimum separation.

The controllers at DCA try to keep the arrivals informed of the other traffic in their vicinity, so that the pilots will have a good idea of what is expected of them to keep traffic moving and why. As a result, pilot cooperation is quite good.

If a potential separation problem arises, the controller can ask for a speed change or a path-stretching maneuver. Air carrier aircraft are not normally asked to perform such actions within the outer marker, but several such instances were observed at DCA in visual conditions. In one case, the pilot asked if the tower would like him

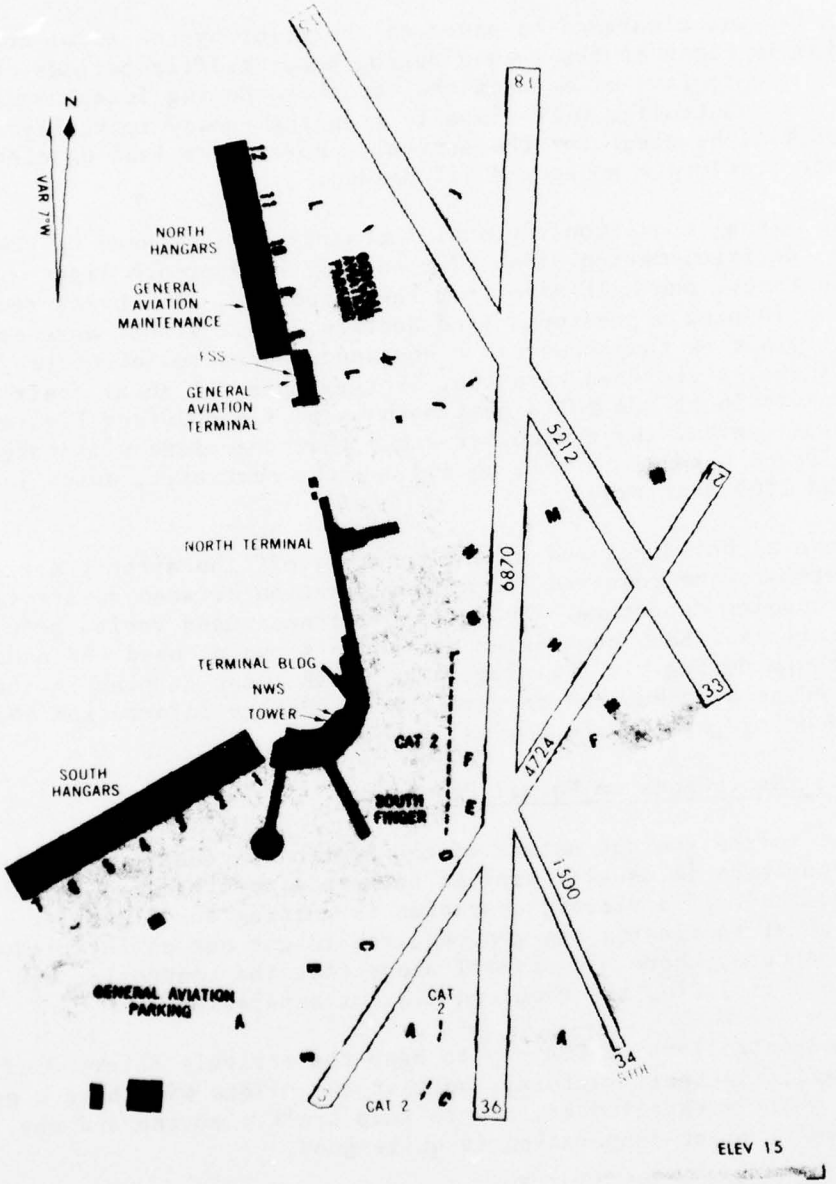


FIGURE A-1
LAYOUT PLAN OF WASHINGTON NATIONAL AIRPORT

to make an S-turn. Smaller general aviation aircraft are more maneuverable and are more likely to receive S-turns or complete 360° turns for spacing purposes.

An additional option which is available to the DCA controllers under the proper conditions is to divert one of the aircraft to a second runway. Runways 15-23 and 3-21 are capable of handling most business and commuter aircraft and even air carrier jets with a moderate headwind.

If this option is unavailable, a go-around may be unavoidable. The controller may ask the aircraft on the runway to advise the tower if he is unable to exit by a particular taxiway. This may lead to a go-around alert, but not necessarily an actual go-around command, for the trail aircraft.

Either the pilot or the controller may initiate the go-around, although neither would be eager to do so. The controller will attempt to deliver the go-around command before the arrival is one-half mile from the threshold, although go-arounds can be initiated as close as the threshold itself. The critical factor is the controller's anticipation of what the aircraft on the runway will do. Although it was not so stated by any of the personnel at DCA, it seems likely that no go-around would be called if the resulting violation of the simultaneous runway occupancy rule were slight and did not affect safety, for example, if the preceding arrival were already turning off far down the runway.

A.4 IMC Procedures

Except for a few items, the above description of what happens in VMC also describes operations in instrument conditions fairly well. Radar separations, rather than visual separations, are of course applied. Since the local controller in the Tower Cab is not a radar position, separation responsibility remains with the final controller until the aircraft is on the runway. If a go-around is required while the aircraft is on the local control frequency, the final controller must coordinate with the local controller through the assistant local controller.

The minimum IFR radar separation between arrivals to DCA is 3.0 nmi because of the absence of heavy aircraft from the fleet (except for 4.0 nmi for a small following a large aircraft). As mentioned above, aircraft are not normally asked for speed changes or other maneuvers inside the outer marker in instrument conditions. The buffer added

by controllers to the minimum separation should avoid the need for this, but this buffer may be reduced in periods of heavy traffic. Consequently, as one controller commented, separations may occasionally drop slightly below the 3.0 nmi minimum (he estimated that less than ten percent were below 3.0 nmi but above 2.5 nmi at the closest). Such operations can be conducted safely at National, because the short runway means that aircraft will usually exit long before the next arrival crosses the threshold, even in IMC. The decision to allow a slight violation of the separation standards is made by the controller on the basis of his experience and knowledge of the airline, aircraft, and pilot involved. It should also be remembered that the judgement that a violation of the standards has occurred is itself a subjective one, given the lack of objective data on aircraft separations.

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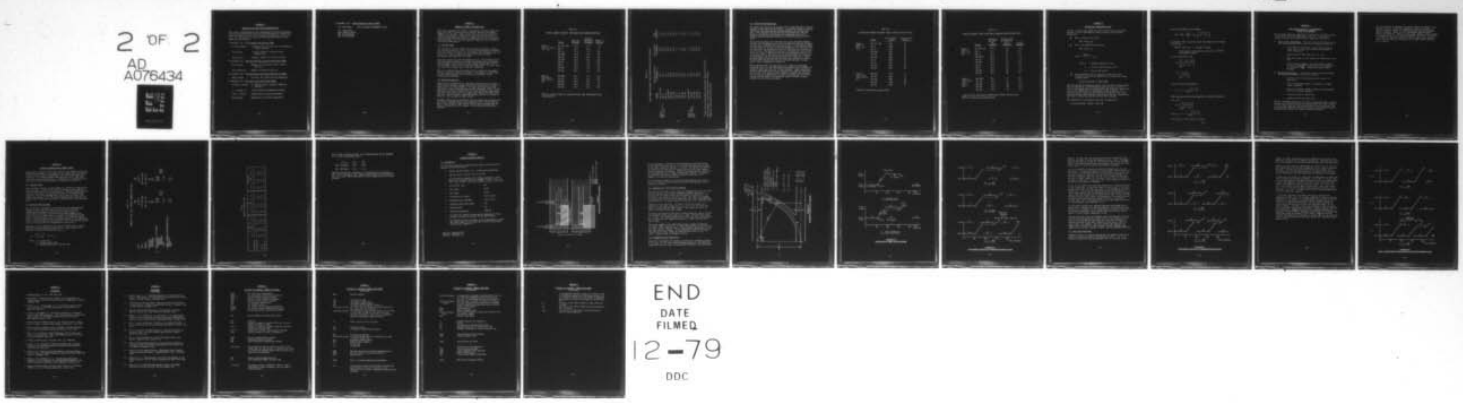

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APPENDIX B

MEETINGS WITH USER GROUP REPRESENTATIVES

Once a basic understanding of the consequences of reduced separations was attained, meetings were held with representatives of several user groups in order to receive their insights and reactions on the subject. The following is a listing of these meetings and the representatives who attended.

2 September 1977 - Air Transport Association (ATA)

William Hardaker	Assistant Vice President for Air Navigation/ Traffic Control
Frank Brady	Director, National Airspace System Engineering
Andrew Pitas	Manager, Terminal Air Traffic Control

8 September 1977 - National Business Aircraft Association (NBAA)

William Horn	Manager of Airspace/Air Traffic Control Services
William Fanning	Manager of Technical Services

8 September 1977 - Aircraft Owners and Pilots Association (AOPA)

Robert Warner	Director, Air Traffic Control Department

9 September 1977 - Air Line Pilots Association (ALPA)

William B. Cotton	Air Traffic Control Technical Committee Chairman
J. J. Ruddy, Jr.	Airport Technical Committee Chairman
John J. O'Brien	Engineering & Air Safety Department
Ed Krupinski	Engineering & Air Safety Department

12 September 1977 - United States Air Force (USAF)

Col. Ward Baker	Chief, Airspace Management Branch
Col. Doyle Kraus	
Maj. Lawrence Taylor	
Maj. William Hardy	
Maj. Grant Hachman	

APPENDIX C

SUMMARY OF RUNWAY OCCUPANCY DATA

Reference 9 presents the results of an analysis of some runway occupancy time data collected by Peat, Marwick, Mitchell and Company (PMM&Co.) for the FAA. These results were used in the analysis of reduced IFR separation standards to assess the feasibility of the maximum average ROCs which would be compatible with the various proposed standards. The following appendix summarizes the information contained in Reference 9.

C.1 The Data Base

The original collection of ROC data was sorted by airport, runway, aircraft group and air carrier. All two and three-engine narrow-body jets were placed in Group 3, all wide-bodied and four-engine jets in Group 4, in order to examine aircraft with similar landing performance characteristics as a body.

Data base entries with obvious apparent errors, such as ROCs greater than one hundred seconds or less than ten seconds, were eliminated. The percentage of such obvious errors ranged from 4% (LGA) to 15% (ATL and DEN). Other entries contained suspect data, but these could not be proved erroneous and so were not eliminated.

Table C-1 contains mean and standard values of ROC for the runways for which sufficient data was available. The number of usable data entries comprising each set is noted as an indication of the reliability of the data.

C.2 Motivated Carriers

Comparison of the ROC data for individual carriers with the layout plans of the different runways verified the existence of a trend: at most airports, airlines tended to use those exits which were most convenient to their terminal gates, within reasonable limits. It was possible to arbitrarily divide carriers into two groups, those which were motivated to exit early on a particular runway, and those which were not. The difference in mean ROC between the two, as listed in Table C-2, was as great as eight seconds.

The ROCs achieved by the motivated carriers present one indication of the level of mean ROC which can be achieved in the current environment. Other carriers could achieve similar ROCs, bringing down the overall average ROC for the runway, if the proper motivation were supplied.

TABLE C-1

OVERALL RUNWAY OCCUPANCY TIME MEANS AND STANDARD DEVIATIONS

	Runway	Mean ROC (Seconds)	Standard Deviation (Seconds)	Number of Records
Group 3 (BAC 111, DC-9, 737, 727)	ATL 27R (26)	51.4	7.5	97
	BUF 5	50.7	13.8	33
	BUF 23	55.9	8.7	124
	DEN 26R*	51.5	8.4	314
	LAX 25L	48.2	10.4	98
	LAX 25R	52.6	14.1	138
	LGA 22	43.3	9.5	315
	LGA 31	40.7	8.5	103
	SFO 28R	47.4	9.2	93
	SFO 28L	49.3	8.1	138
Group 4 (707, DC-8, L1011, DC-10, 747)	DEN 26R*	55.1	9.4	100
	LAX 25L	50.9	9.6	150
	LAX 25R	60.2	16.8	50
	SFO 28R	57.5	16.5	61
	SFO 28L	55.0	13.4	130

*DEN 27L, normally used for larger aircraft, was closed during the survey period.

TABLE C-2

MEAN RUNWAY OCCUPANCY TIME OF MOTIVATED AND OTHER CARRIERS

	Runway	Motivated Carriers* (Seconds)	Other Carriers (Seconds)	Δ ROC (Seconds)
Group 3 (BAC 111, DC-9, 737, 727)	ATL 27R (26)	49.5	52.8	3.3
	BUF 5	47.1	55.5	8.4
	BUF 23	52.3	57.6	5.3
	DEN 26R***	48.4	53.6	5.2
	LAX 25L	44.9	51.3	6.4
	LAX 25R	50.5	57.4	6.9
	LGA 22	43.3	**	**
	LGA 31	40.7	**	**
	SFO 28R	46.3	49.7	3.4
	SFO 28L	49.1	49.7	0.6
Group 4 (707, DC-8, L1011, DC-10, 747)	DEN 26R***	55.1	**	**
	LAX 25L	49.6	51.3	1.7
	LAX 25R	57.3	62.5	5.2
	SFO 28R	56.0	59.6	3.6
	SFO 28L	53.4	59.0	5.6

*Those carriers motivated by operational factors to exit early

**No differences in motivational patterns surfaced

***DEN 27L closed during survey period

C.3 Potential ROC Reductions

The report also analyzed the minimum level of mean ROC which could be expected without major modifications. A theoretical model of runway occupancies was developed and compared against the available ROC data. The comparison showed that actual performance at the predominant exit matched the theoretical performance fairly well, assuming moderate braking followed by rolling deceleration to exit speed.

The theoretical model also indicated that, with continued moderate braking, well-designed exits as close at 4300 feet from the threshold could be used, with ROCs less than 40 seconds. A substantial number of observations of aircraft using high speed exits at 4300 feet from the threshold, and conventional exits at 4500 feet were recorded in the data base. Consequently, exits were identified at other airports which lay closer to the threshold than the predominant exit but no closer than 4300 or 4500 feet, and the potential ROC for these exits was determined from the theoretical model (see Table C-3). These potential ROCs at the more efficient exits are substantially below the mean ROCs observed even for the motivated carriers, in most cases. This is tabulated in Table C-4.

These potential ROCs are sufficient in all cases for acceptable operations with a 2.5 nmi IFR separation standard, and in almost all cases for operations with the 2.0 nmi standard. These values were obtained using existing exits and assuming just moderate braking by the aircraft. The question which remains is whether the airlines will be willing to modify their current procedures and incur extra taxiing time by taking less convenient exits, in order to save another aircraft from a go-around.

TABLE C-3

LOCATION AND RUNWAY OCCUPANCY TIMES OF MORE EFFICIENT EXITS

	Runway	Exit Distance (Feet)	Potential ROC Seconds)
Group 3 (BAC 111, DC-9, 737, 727)	ATL 27R (26)	5124	42
	BUF 5	4665	38
	BUF 23	4768	38
	DEN 26R*	5087	41
	LAX 25L	4607	37
	LAX 25R	4666	38
	LGA 22	4955	41
	LGA 31	4291	36
	SFO 28R	5664	46
	SFO 28L	5802	46
Group 4 (707, DC-8, L1011, DC-10, 747	DEN 26R*	5087	41
	LAX 25L	4607	37
	LAX 25R	4666	38
	SFO 28R	5664	46
	SFO 28L	5802	47

*DEN 26L closed during survey period

TABLE C-4

RUNWAY OCCUPANCY TIMES OF MOTIVATED CARRIERS AND EFFICIENT EXITS

	Runway	Motivated Carrier* ROC (Seconds)	Potential ROC At Efficient Exit (Seconds)	Δ ROC (Seconds)
Group 3 (BAC 111, DC-9, 737, 727)	ATL 27R (26)	49.5	42	7.5
	BUF 5	47.1	38	9.1
	BUF 23	52.3	38	14.3
	DEN 26R**	48.4	41	7.4
	LAX 25L	44.9	37	7.9
	LAX 25R	50.5	38	12.5
	LGA 22	43.3	41	2.3
	LGA 31	40.7	36	4.7
	SFO 28R	46.3	46	0.3
	SFO 28L	49.1	46	3.1
Group 4 (707, DC-8, L1011, DC-10, 747)	DEN 26R**	55.1	41	14.1
	LAX 25L	49.6	37	12.6
	LAX 25R	57.3	38	9.3
	SFO 28R	56.0	46	10.0
	SFO 28L	53.4	47	6.4

*Those carriers motivated by operational factors to exit early

**DEN 26L closed during survey period

APPENDIX D

THEORETICAL INTERVENTION RATE

In order to derive the theoretical rate of controller intervention required to avoid simultaneous runway occupancy, we make three assumptions:

- ROC is normally distributed

  $$ROC = N(\mu_R, \sigma_R)$$

- IAT is also normally distributed

  $$IAT = N(\mu_I, \sigma_I)$$

  $$\text{and } \mu_I = \frac{3600 * S}{V} + z_I \sigma_I$$

  where S = minimum separation in nmi

  V = trail aircraft velocity in kt

  z_I = size of IAT buffer

- an intervention will be required *if and only if* the interarrival time would otherwise be less than the runway occupancy time

  $$P\,[\text{intervention}] = P\,[IAT < ROC]$$

Both IAT and ROC are measured from the time the first aircraft passes over the threshold, so IAT < ROC means that the first aircraft is still on the runway when the second passes the threshold. This would violate the prohibition on simultaneous runway occupancy, if it occurred, and so controller intervention is required. This intervention may take several forms; a go-around is the most extreme case, and hence is used only when there are no other options.

The probability of intervention can also be expressed as

$$P\,[\text{intervention}] = P[(IAT - ROC) < 0]$$

Since IAT and ROC are both normal,

$$(IAT - ROC) = N\left(\mu_I - \mu_R, \sqrt{\sigma_I^2 + \sigma_R^2}\right)$$

and $P[(IAT - ROC) < x]$ can be found from tables of the normal distribution

$$P[(IAT - ROC) < x] = 1 - \phi(-z_{IN}) = \phi(z_{IN})$$

where $\phi(z_{IN})$ = intervention rate, and $z = \left|\frac{x - \mu}{\sigma}\right|$, a standard variable.

For this particular case,

$$z_{IN} = \left| \frac{0 - (\mu_I - \mu_R)}{\sqrt{\sigma_I^2 + \sigma_R^2}} \right|$$

$$z_{IN} = \frac{\mu_I - \mu_R}{\sqrt{\sigma_I^2 + \sigma_R^2}}$$

which can also be expressed as

$$\mu_R = \mu_I - z_{IN}\sqrt{\sigma_I^2 + \sigma_R^2}$$

where μ_R would be the value required to achieve a desired z.

For $x \neq 0$

$$z_E = \left| \frac{\mu_R - \mu_I + x}{\sqrt{\sigma_I^2 + \sigma_R^2}} \right|$$

and $\mu_R = \mu_I - x - z_E\sqrt{\sigma_I^2 + \sigma_R^2}$

where $\phi(z_E)$ = "event rate" for time x.

APPENDIX E

PRELIMINARY DESIGN OF A COMPREHENSIVE SURVEY OF GO-AROUNDS

The following items are suggested for inclusion in any future survey of go-arounds and missed approaches. This list is intended to include all items of interest, without regard for feasibility.

A. Total Traffic Information -- for each time period (hour or less), the tower supervisor should record the following information:

- -- total number of approaches, broken down by type of runway use (arrivals only, mixed arrival-departure, mostly departures)
- -- general weather (VMC, IMC, CAT I, II, III)
- -- ATC control mode (visual separation, IFR delivery, full IFR)
- -- traffic density (heavy - aircraft holding, minimum separations; medium - minimum separations common but not universal; light - separations usually above minimum)

B. Go-around Information -- for each go-around or missed approach, the following information should be recorded:

- -- aircraft type (of preceding aircraft as well, if pertinent)
- -- cause of go-around (weather, overtaking in flight, runway occupancy)
- -- point of initiation (height, distance from threshold, position in landing sequence)
- -- initiator (pilot or controller)
- -- runway use (arrivals only, etc.)

Similar information should be collected for go-arounds which occurred but were not necessary (either no procedure would have been violated or else safety would not have been affected by such violation), and for successful approaches which should have been go-arounds (either a procedure was violated or a safety hazard was created).

The survey should be conducted for several months at several of the busiest airports. Controller cooperation could be a problem. A system of amnesty similar to the Aviation Safety Reporting System might be required. Also, a lot of information and some subtle details are asked for. Special survey teams, however, would probably be impractical due to the required length of the survey. Two shifts a day would be required, perhaps for several months (the midnight shift would not need to be covered, due to light traffic levels at most airports).

APPENDIX F

OBSERVED COMMUNICATIONS CHANNEL USAGE

A preliminary analysis of the local control voice channel at National Airport was performed in an attempt to obtain some objective measures of the channel congestion problem posed by reduced IFR separation standards. Two one-hour samples were obtained, one for VFR conditions and one for IFR conditions. Information on the sample periods, and on the observed channel usages, is presented in Table F-1.

F.1 Message Length

Each individual message in these samples was timed and categorized by type and origin. It was found that the average message length was less than two seconds in all circumstances. Message lengths were not normally distributed, but instead were closer to a Gamma distribution, with the shorter messages more likely than the longer ones. Ninety-nine percent of all the observed messages were less than 4.8 seconds long in VMC, and less than 6.5 seconds long in IMC (see Table F-2).

F.2 Expected Waiting Times

One of the basic questions to be answered by this communications channel analysis was the following: with the present radio communications system, will the controller have to wait an unacceptably long time to deliver the go-around command to the pilot? One way to answer this is to look at the expected waiting time for the controller to use the channel, as derived by queuing theory. Since the controller can interrupt himself at any time while he is using the channel, we are interested only in the periods during which it is being used for transmissions by the pilots.

Approximating the communications system as an M/G/1 queue (random arrivals, a general service process, and a single server), the equation for expected waiting time, W_q, is:

$$W_q = \frac{\lambda(b^2 + \sigma_t^2)}{2(1 - \lambda b)} \quad \text{for } \lambda b < 1$$

where λ = arrival rate
b = average service time
σ_t = standard deviation of service time

TABLE F-1

SUMMARY OF DCA LOCAL CONTROL COMMUNICATION TAPES

	VMC		IMC	
DATE:	8-18-77		8-24-77	
TIME:	1700-1759 EDT		1500-1559 EDT	
RUNWAYS:	R36, R33, R3		R36, R33, R3	
OPERATIONS:	81		56	
ARRIVALS	32		27	
DEPARTURES	49		29	
VOICE CHANNEL UTILIZATION	39.6%		42.8%	
CONTROLLER	27.5%		30.9%	
ARRIVALS		12.1%		18.4%
DEPARTURES		15.4%		12.5%
PILOT	12.1%		11.9%	
LONGEST TRANSMISSION DURATION (SEC.)				
CONTROLLER	7.8		11.1	
PILOT	11.2		11.5	

TABLE F-2

OBSERVED PILOT MESSAGE LENGTHS

	VMC			IMC			VMC & IMC		
	arr	dep	all	arr	dep	all	arr	dep	all
99th percentile	6.1 sec.	4.4 sec.	4.8 sec.	5.7 sec.	6.5 sec.	6.5 sec.	5.8 sec.	4.4 sec.	5.7 sec.
95th percentile	3.8	4.2	3.3	3.6	2.6	3.3	3.7	2.6	3.3
n	142	180	322	161	119	280	303	299	602
mean (b)	1.65	1.13	1.36	1.69	1.33	1.54	1.67	1.21	1.44
std. devl (σ_t)	1.36	0.75	1.09	1.29	0.94	1.17	1.32	0.83	1.13

For the data collected at DCA, the following values can be assigned to λ, b and σ_t (from Table F-2):

	λ	b	σ_t
VMC	322/3600s	1.36s	1.09s
IMC	280/3600s	1.54s	1.17s

Expected waiting time, therefore, is calculated as 0.15 seconds in VMC and 0.17 seconds in IMC. These extremely small waiting times are due to the small number and generally short length of pilot-oriented messages.

APPENDIX G

STAGGERED APPROACH ANALYSIS

G.1 Assumptions

The following simplified assumptions were made for the analysis of staggered arrival operations

- -- present day ATC system (*i.e., no Metering and Spacing*)
- -- approach speed = 140 kts for all aircrft
- -- all arrivals are spaced at the average separation, which equals the minimum separation standard (3.0 nmi = 77s, 2.5 nmi = 64s, 2.0 nmi = 51s) *plus a buffer of* 30s (1.65 X 18s)
- -- arrival ROC (μ_R) 55s
- -- exit speed 35 kt.
- -- taxi speed 20 kt.
- -- deceleration in curve* 0.8 ft./sec.^{2}
- -- deceleration on straight* 5.0 ft./sec.^{2}
- -- crossing runway from *stop*** 30s
- -- departure ROC 35s
- -- centerline separation 1000 ft.
- -- *all exits are ideally located and are designed to allow aircraft to easily hold short of the inner runway.*
- -- the taxiway system is designed to allow departures to avoid the glide slope critical area, and to avoid interference with arrivals (Figure G-1)

*Source: Reference 19
**Source: Reference 22

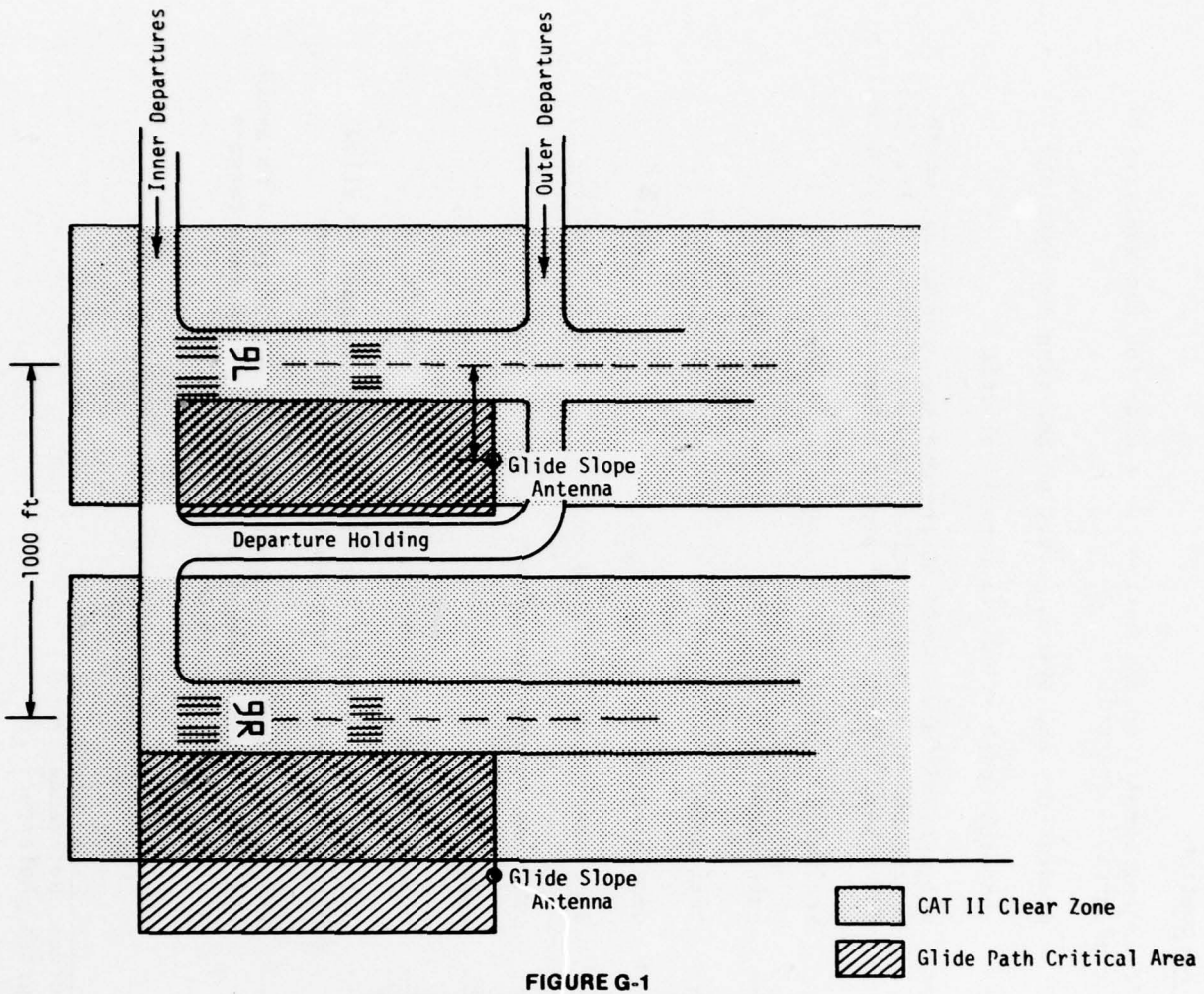


FIGURE G-1
POSSIBLE NON-CONFLICTING TAXIWAYS

The exit geometry in Figure G-2 was developed to determine theoretical times from runway exit to a full stop, 200 feet from the edge of the inner runway (27 seconds -- a value of 30 seconds was used in the analysis) and from exit to crossing clear of the inner runway without stopping (42 seconds). Some of the design details came from the proposed new exits at Miami International Airport. The design here has been simplified, however (constant radius turns, for example), to ease the calculations.

The calculations themselves are not presented because they consist solely of repeated, detailed application of simple geometry and the equations of motion.

G.2 Explanation of the Time-Line Diagram

This analysis will make use of time-line diagrams which plot aircraft position against time to depict staggered approach operations. Aircraft on the runway surface move through four dimensions: two horizontal, one vertical, and one in time. The time-line diagrams are rough plots of two of these dimensions; the y-axis shows movement perpendicular to the runway centerline, and the x-axis indicates time.

Figure G-3 will illustrate. In Case A, arrival A1 crosses the threshold of the outer runway at t = 0. At t = 55s, A1 exits and taxis to and crosses the inner runway. This takes 45s, so at t = 100s A1 is clear of the inner runway.

Arrival A2 was spaced 3.0 nmi plus a buffer behind A1, and so crosses the threshold of the inner runway at t = 107s. A2 exits 55s later, at t = 162s. The runway system is then idle until A3, 3.0 nmi behind A2, crosses the outer runway threshold at t = 214s, and the cycle begins again.

The second example in the same Figure shows a slightly different situation. Here A2 arrives at t = 90s, requiring A1 to hold short of the inner runway. When A2 exits, A1 moves again, taking 30s to cross and clear the inner runway. In the meantime, a departure has been released on the outer runway 10s after A2 arrives (i.e., at t = 100s). Departure ROC is assumed to be 35s.

G.3 Staggered Arrival Operations

Figure G-4 illustrates the sequence of events for staggered arrivals at 3.0 nmi, 2.5 nmi, and 2.0 nmi minimum separations. Reducing the separations does not cause any significant changes in the operational

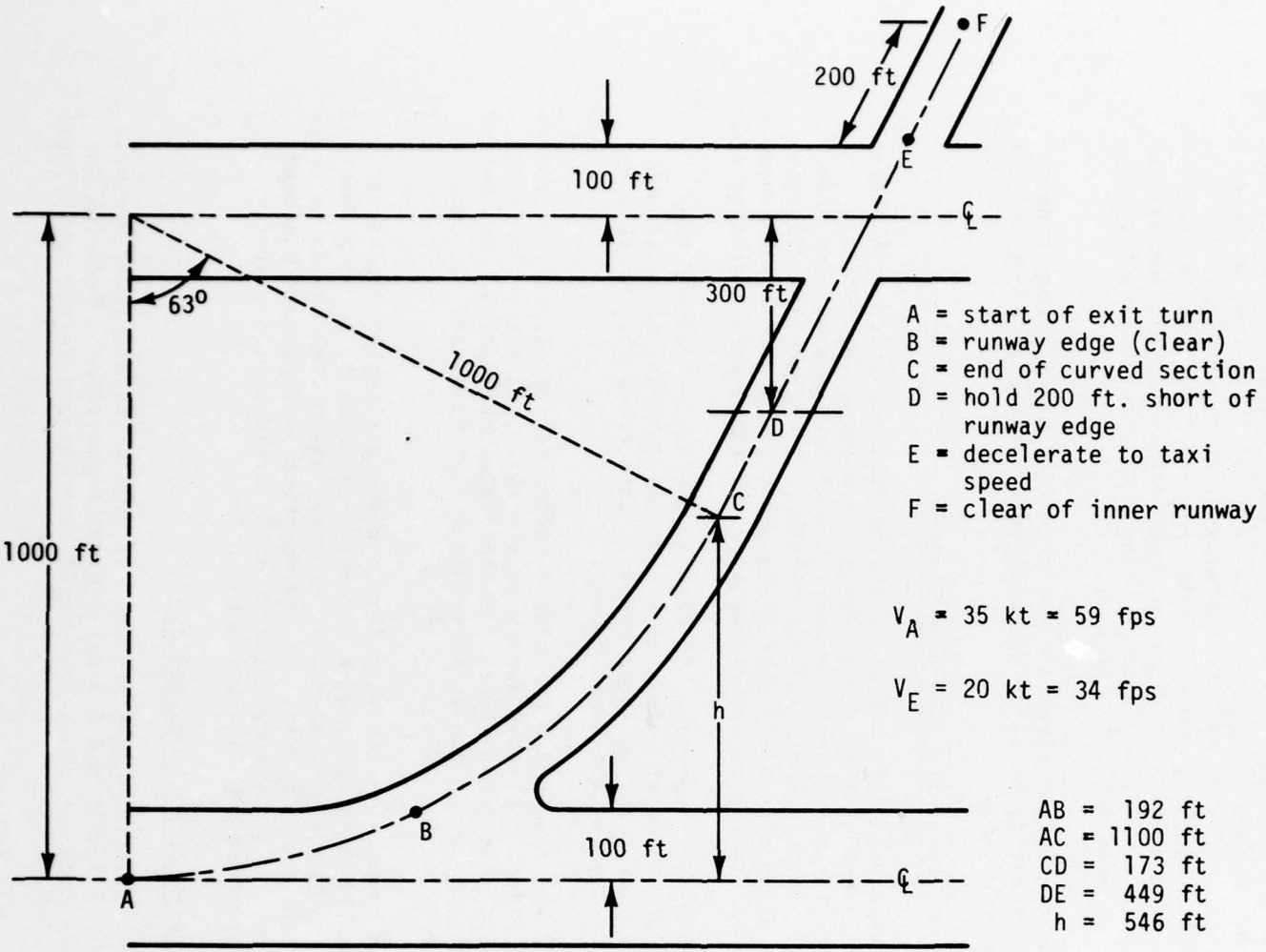
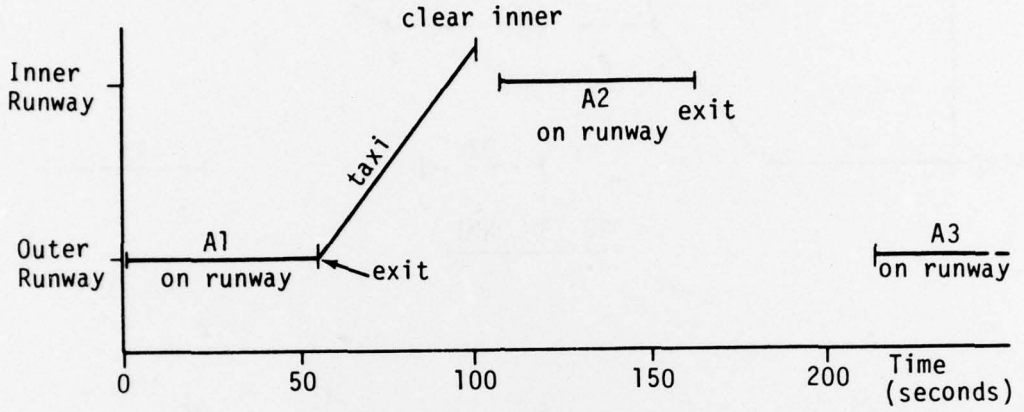
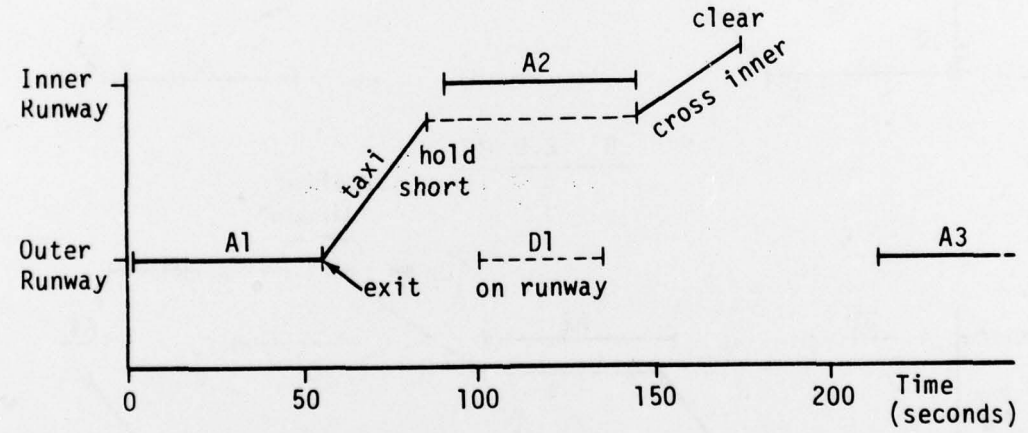


FIGURE G-2
ASSUMED RUNWAY EXIT DESIGN



A. ARRIVALS ONLY



B. MIXED OPERATIONS

FIGURE G-3
EXAMPLES OF TIME-LINE DIAGRAMS

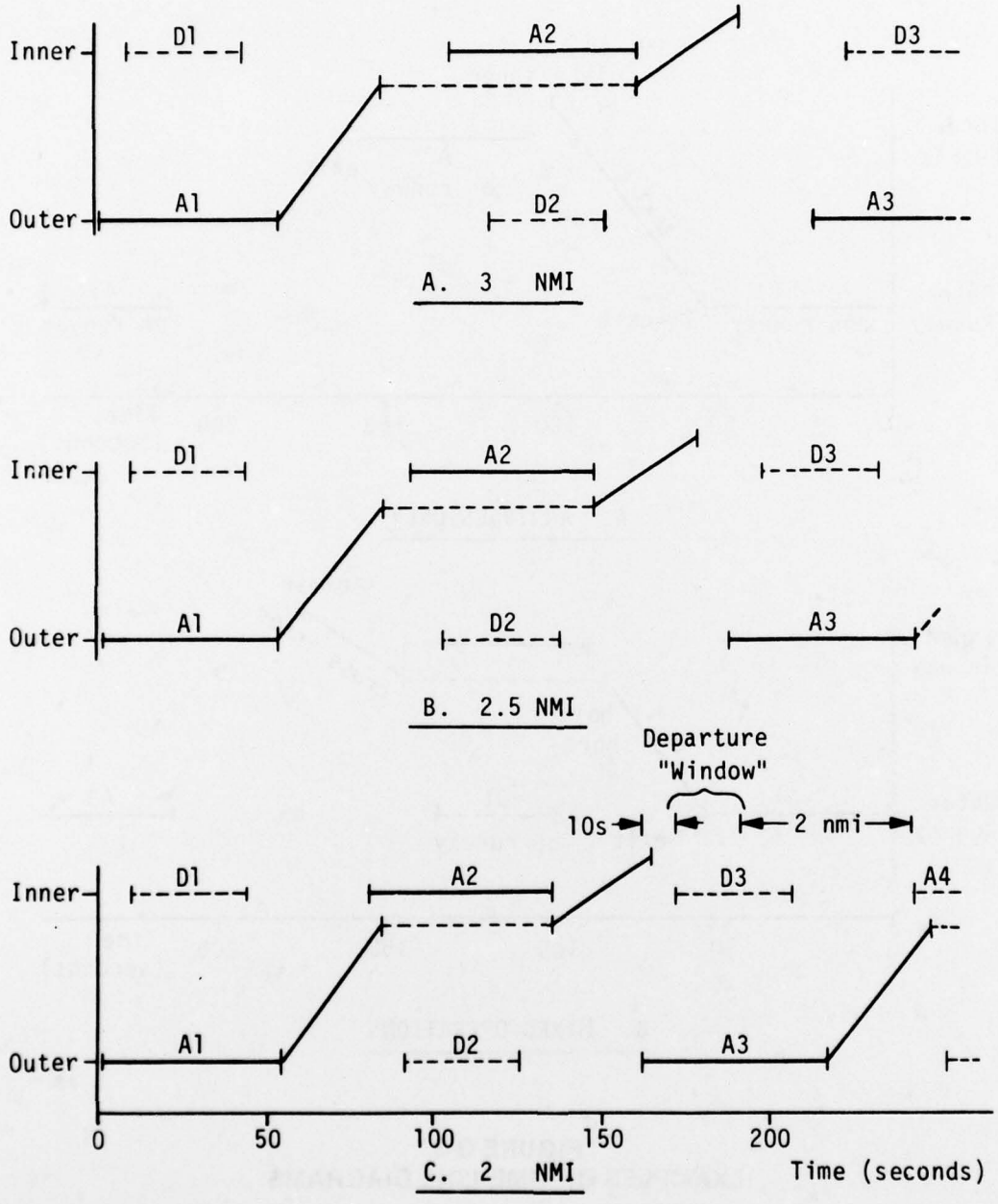


FIGURE G-4
STAGGERED ARRIVALS AT REDUCED SEPARATIONS

pattern. In each case, the arrival on the outer runway must hold short of the inner to allow the inboard arrival to land. Although it would be possible at 3.0 nmi for the outer arrival to taxi straight across, only seven seconds would then separate the operations on the inner runway; it is felt that this would not be adequate.

It is also possible to sequence a departure between each pair of arrivals, at each minimum separation, even though several constraints must be met. A departure cannot be released before the arrival on the other runway is committed to land, which we have assumed to be 10s after threshold crossing. Nor can it be released if the next arrival, to either runway, is less than 2.0 nmi from the threshold, according to IFR rules. Even at 2.0 nmi, a 20s departure "window" is available, which should be adequate.

So far arrival separations have been assumed to be constant and equal to the average IAT. It would be useful to look as well at the more extreme case, where all IATs were equal to the minimum value instead (Figure G-5). At 2.5 nmi no departures would be possible on the inner runway because when the outboard arrival had cleared the inner runway, the next inboard arrival would be less than 2.0 nmi from the threshold. On the outer runway, the probability of a departure would be small because the departure "window" would be a scant three seconds long. At 2.0 nmi separations, the 2.0 nmi departure-arrival rule would prevent any departures at all.

As individual aircraft pair spacings approach the minimum, which would occur occasionally in actual operations, some departure gaps could be lost. However, this is preferrable in terms of time, fuel, and control complexity to a go-around, which would be the likely result if only a single runway were in use.

This has admittedly been an extremely simplified analysis, based on unrealistic fixed operational times, but it is encouraging to note that no severe operational problems have thus been discovered. Outboard arrivals do not need a special arrival gap to cross the inner runway, for example. Nor was a special gap required for departures to cross to the outer runway; instead, adequate time seemed to be available between arrivals, even at minimum separations.

G.4 Dual Lane Operations

Staggered arrivals at reduced separations are possible today if the parallel runways are separated by 3000 feet or more. For closer parallels, operations may be performed, with all arrivals on one

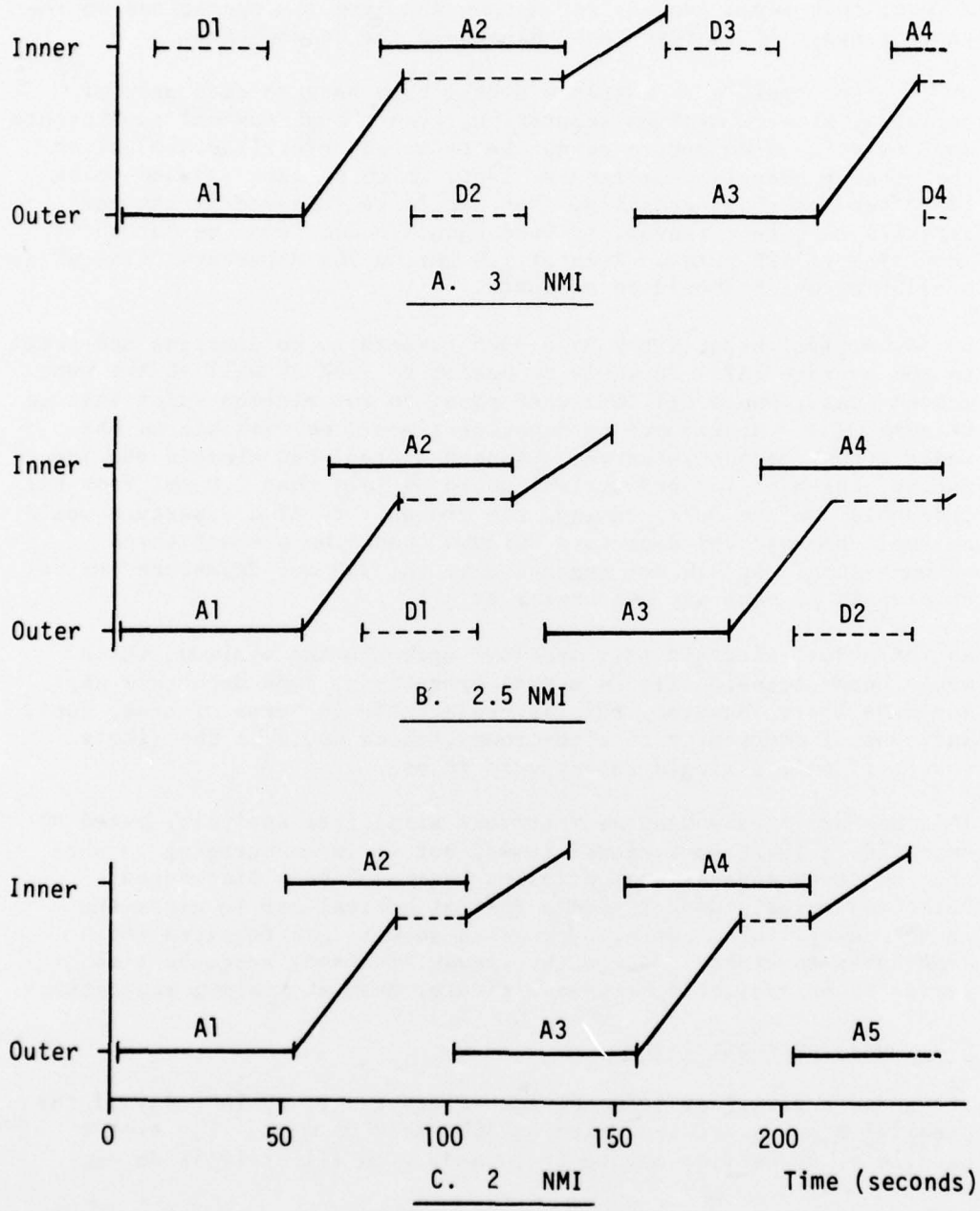


FIGURE G-5
STAGGERED ARRIVALS AT MINIMUM SEPARATIONS

runway (at normal separations) and all departures on the other (see References 19 and 23 for a complete discussion). The question arises then, are staggered arrivals more effective than dual-lane operations?

Figure G-6 charts dual-lane operations at 3.0 nmi, 2.5 nmi, and 2.0 nmi separations using the same assumptions as our study of staggered arrivals. Arrivals have been placed on the outer runway, which simulations of dual-lane operations have indicated to be "the most easily workable and flexible configuration" (Reference 19, page 84).

A comparison with Figure G-4 shows that the same number of operations can be conducted with either procedure. At 3.0 nmi or 2.5 nmi separations, dual-lane would probably be preferred for its reduced ground control requirements: arrivals are free to taxi across the inner runway, and departures need not cross the inner. At 2.0 nmi, however, the outboard arrivals must be held short of the inner runway (e.g., A2) or else only an eight second departure "window" would be available (e.g., D2). Placing arrivals on the inboard runway would, of course, avoid this problem.

If dual-lane operations are simpler and just as efficient as staggered arrivals, why even consider staggered arrivals at reduced separations? The reason is a problem which does not show up in these analyses: go-arounds to avoid simultaneous occupancy due to the variations in actual ROCs and IATs. The conclusion presented in earlier sections holds just as well for dual-lane runways as for single runways -- in order to keep the intervention rate at acceptable levels when separations are reduced, runway occupancy times must also be reduced. Staggered arrivals are a possible alternative procedure for operations on dependent runways when the necessary ROC reductions cannot be achieved in all cases. Staggered arrivals transfer the penalty of a long ROC, or a short IAT, for an occasional arrival from a go-around for the trail arrival to a possibly missed departure gap.

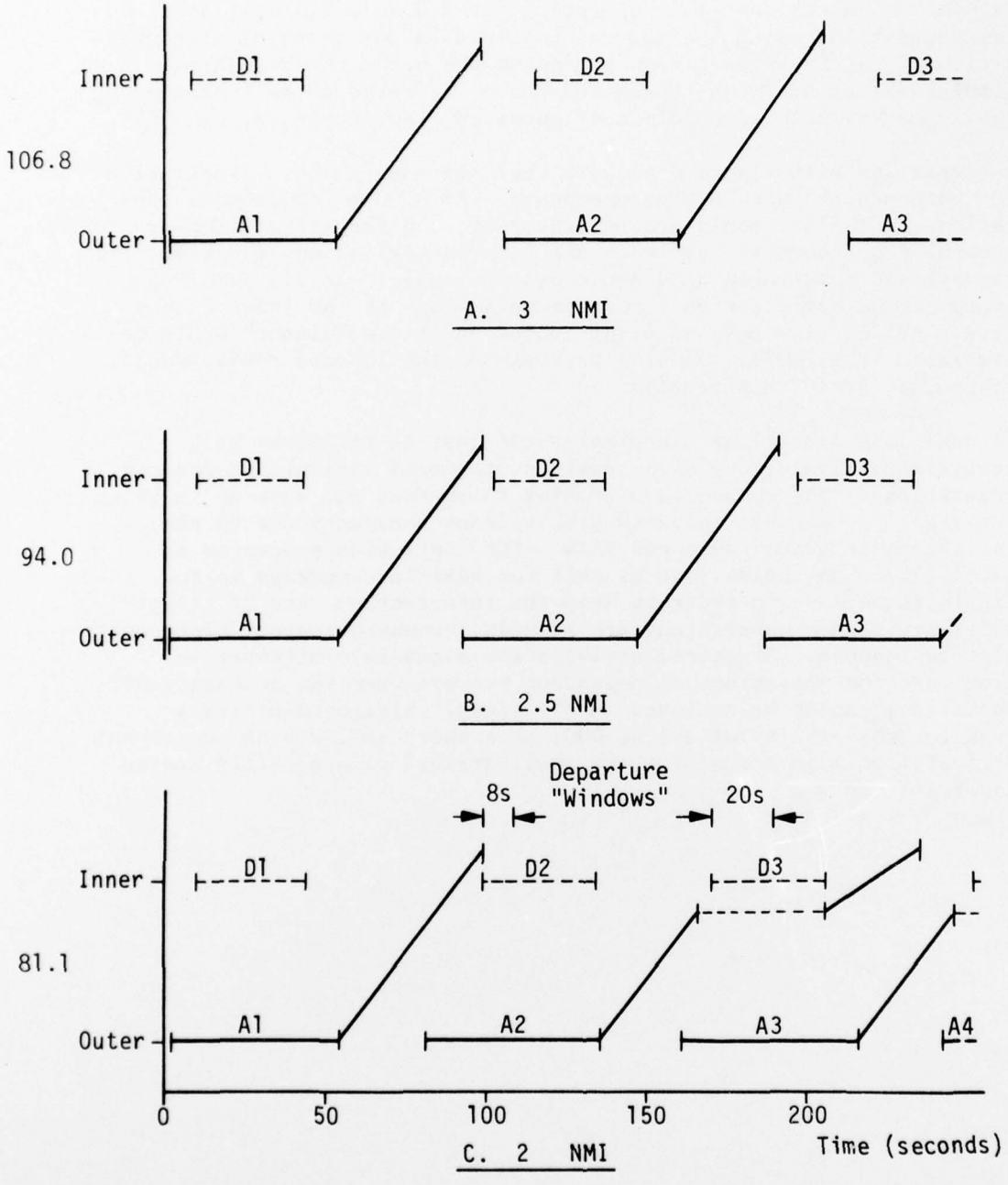


FIGURE G-6
DUAL-LANE RUNWAY OPERATIONS AT REDUCED SEPARATIONS

APPENDIX H

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APPENDIX I

GLOSSARY OF ACRONYMS, SYMBOLS AND TERMS

ALPA	Air Line Pilots Association
AOPA	Aircraft Owners and Pilots Association
ARTS III	Automated Radar Terminal System
ASDE	Airport Surface Detection Equipment
ASTC	Airport Surface Traffic Control
ATA	Air Transport Association
ATC	Air Traffic Control
ATCAC	Air Traffic Control Advisory Committee
ATCRBS	Air Traffic Control Radar Beacon System
ATL	Atlanta Hartsfield International Airport
BUF	Greater Buffalo International Airport
CAP	Capacity
CAT I	Category I weather, minima of 200 feet decision height and 1800 feet RVR.
CAT II	Category II weather, minima of 100 feet decision height and 1200 feet RVR.
CAT III	Category III weather, with zero/zero minima.
CDTI	Cockpit Display of Traffic Information
DABS	Discrete Address Beacon System
DCA	Washington National Airport
DEN	Denver Stapleton International Airport
Event Rate	The probability that an arrival is still on the runway when the next arrival is one-half mile from the threshold, assuming heavy traffic and no prior controller intervention.
FAA	Federal Aviation Administration
4D	Four-dimensional RNAV (includes time)
Go-around	An approach which is aborted in order to avoid simultaneous runway occupancy. Not the same as missed approach.

APPENDIX I

GLOSSARY OF ACRONYMS, SYMBOLS AND TERMS
(continued)

HUD	Head Up Display
IAT	Interarrival Time
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
Interarrival Time	The time interval between arrivals, measured as they pass over the threshold.
Intervention Rate	The probability that the IAT between two aircraft is less than the ROC of the first one, and therefore controller intervention is needed to prevent simultaneous runway occupancy.
kt	Knots, nautical miles per hour
LGA	LaGuardia Airport
LAX	Los Angeles International Airport
M&S	Metering and Spacing
Missed Approaches	A landing attempt which is aborted due to poor visibility conditions
MLS	Microwave Landing System
MTR	MITRE Technical Report
μ_I	Average IAT
μ_R	Average ROC
NASA	National Aeronautics and Space Administration
NBAA	National Business Aircraft Association
nmi	Nautical mile
OSEM	Office of Systems Engineering Management
$\phi(z)$	The cumulative value of the normal distribution; specifically, the size of the tail of the distribution at a point z standard deviations from the mean.

APPENDIX I

GLOSSARY OF ACRONYMS, SYMBOLS AND TERMS
(continued)

Reference Runway	A runway whose occupancy time characteristics are such that any degradation in ROC requires an increase in the minimum IFR arrival separation.
Reference Runway Concept	The idea that it should be feasible to conduct arrivals continuously at precisely the minimum arrival separation without more than a limited number of go-arounds.
RNAV	Area Navigation
ROC	Runway Occupancy Time
Runway Occupancy Time	The interval between crossing the threshold and exiting the runway.
RVR	Runway Visual Range
S	Minimum interarrival separation
s	Second
SFO	San Francisco International Airport
σ_I	Standard deviation of interarrival time
σ_R	Standard deviation of runway occupancy time
TAGS	Tower Automated Ground System
TCA	Terminal Control Area
USAF	United States Air Force
V	Velocity (on final approach)
VAS	Vortex Advisory System
VASI	Visual Approach Slope Indicator
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
WVAS	Wake Vortex Avoidance System

APPENDIX I

GLOSSARY OF ACRONYMS, SYMBOLS AND TERMS
(concluded)

z	A standardized variable, equal to $\lvert(x-\mu)/\sigma\rvert$, used to transform a normally distributed variable x to fit standard tables; also, the number of standard deviations in a buffer to produce the probability $\phi(z)$.
z_E	The size of the buffer needed to keep event rate constant.
z_{IN}	The size of the buffer needed to keep intervention rate constant.
z_{IAT}	The size of the IAT buffer resulting from the control system employed.