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Institute of Transportation Studies
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Research Report

MEASURES TO INCREASE AIRFIELD CAPACITY BY CHANGING AIRCRAFT RUNWAY OCCUPANCY CHARACTERISTICS

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EXECUTIVE SUMMARY

Background and Objectives

In the late 1970's and early 1980's, airport congestion became a significant problem; causing delays to passengers, increased aircraft operating costs for airlines, and increased workload for air traffic control. Complicating the situation were the changes that were occurring in the mix of aircraft using the nation's large hub airports. An increasing proportion of wide-bodied jets brought increased problems of wake turbulence; while an increasing number of commuter, air taxi, and general aviation aircraft brought variations in approach speed and aircraft operating characteristics to these airports.

NASA and FAA recognized these problems and undertook research, engineering, and development programs designed to alleviate the congestion. Part of this program included the research conducted by the University of California and described in this report. The goal of this research was to reduce the impact of aircraft runway occupancy on airport congestion today and in the future.

There were four specific objectives identified for the study. The first objective was to develop a more complete understanding the various factors that affect runway occupancy. The second objective was to identify promising innovations for aircraft, airports, air traffic control, and pilots that would assist in reducing airport congestion. The third objective was to define the research, engineering, and development activities required to implement the innovations identified above. The fourth objective was to assess the impact of technology developments in the area of short-haul aircraft and air traffic control measures.

Runway Occupancy and Airport Congestion

While the study was aimed directly at runway occupancy and ways of reducing runway occupancy time, it was recognized that the overall objectives related to reducing airfield congestion. Therefore, the influence of runway occupancy on airport congestion was one of the first items addressed in the study.

It became clear that there were three major ways that runway occupancy could be affected. First, the mean runway occupancy time for aircraft could be reduced. Secondly, the variation of runway occupancy times for individual aircraft about the mean could also be reduced, i.e., reduced standard deviation. Thirdly, two aircraft might be permitted to use a runway at the same time, thereby reducing the effective runway occupancy time.

Each of these three items would permit gains in runway capacity. These gains in runway capacity would result in reductions in aircraft delay, and consequent reductions in operating costs, fuel consumption, and the need for demand management. Recent estimates of airfield congestion indicate that up to $1 billion per year is being paid by the airlines in increased aircraft operating cost due to airfield congestion. This study indicates that up to $75 million per year of this increased aircraft operating cost might be saved today by reduced runway occupancy, with much larger savings possible in the future.

Factors Influencing Runway Occupancy

Runway occupancy starts when an aircraft crosses the runway threshold and ends when the aircraft leaves the runway. The process of transition from flight to ground taxiing is complex, and depends upon a number of factors.

Approach speed influences runway occupancy time, and normally the greater the approach speed the greater the runway occupancy time. The distance from the runway threshold at which the aircraft touches down also influences runway occupancy time because significant aircraft deceleration normally begins after the aircraft has touched down. The aircraft deceleration process then commences, after a pause for the pilot to confirm a safe landing and to spool up the engines in reverse thrust. The amount of aircraft deceleration depends on pilot technique, pavement condition, and aircraft reverse thrust and braking characteristics. Another major influence on runway occupancy time is the location and design of the runway exit. Exit width, angle, and length can all influence exit speed, which may be up to 60 knots for some aircraft on appropriately designed exits. Exits must be located in a suitable position for the individual aircraft in order to take full advantage of the aircraft's deceleration characteristics. Typical runway occupancy times for large jet transport aircraft are in the order of 45 to 65 seconds.

Potential Innovations

The research uncovered a number of potential innovations designed to reduce the influence of runway occupancy on airfield capacity. The innovations can be classified into four general areas:

- Aircraft Innovations
- Airport Innovations
- Pilot Innovations
- ATC/FAR Innovations.

A large number of potential innovations were identified in each area, and were subjected to a preliminary assessment. Based on this assessment, promising innovations were grouped into packages with similar characteristics. Each of these packages is discussed briefly below.

Improved Short-Haul Aircraft Technology. Changes in aircraft technology and design could assist in making better use of existing airports. Characteristics of the package of innovations include enhanced deceleration and acceleration, improved exit turn capability, reduced touchdown and liftoff speeds, and improved go-around performance. These characteristics would require improved brakes and landing gear and some active control integration. Up to 25 seconds reduction in runway occupancy time might be obtained with up to 10% gains in runway capacity.

Pilot and Airline Motivation. This package recognizes that incentives or motivation concerning runway occupancy may assist in optimizing runway use. The two major alternatives considered are pricing runway time as an economic incentive, and modifications to ATC and flight rules to require aircraft to meet certain performance criteria. Some sophisticated time measurement and accounting techniques would be necessary in order to be able to implement either type of innovation. Decreases in the order of 10 seconds might be obtained in runway occupancy time with increases in runway capacity of approximately 5%.

<u>Pilot and Controller Information.</u> This package recognizes that provision of additional and more precise information to pilots and controllers can help them make improved decisions to take full advantage of available facilities. Improved exit selection and runway deceleration profiles could be obtained, partly from enhanced precision on the approach and through improved cockpit instrumentation and approach aids. An automated headway display system would be necessary to provide the pilot with data about preceding aircraft, and automated departure release and/or go-around advisories might be appropriate. Up to 15 second reductions in runway occupancy time could be obtained from this improvement, with up to 10% gains in runway capacity.

<u>Runway Exit and Entrance Design.</u> This package contains revised exit location criteria and geometry, continuous exits, adequate runout clearances on high speed exits, and high speed runway entrances. The combination of these items could obtain up to 30 seconds reductions in runway occupancy time and obtain gains of up 10% in runway capacity. Improved dynamic exit lighting systems would be required, as would new design criteria for continuous exits.

<u>Dense Airfield Operation.</u> This package is designed to make full use of the existing pavement at an airport and to add extra pavement to the existing airfield where appropriate. The existing taxiways might be used as runways and as exit deceleration zones in order to assist aircraft in leaving the runways at higher speeds. Displaced thresholds, intersection takeoffs, and use of converging and close parallel runways for additional runway operations would also be involved. Additional

pavement might include close parallel and short runways, additional exits (including continuous exits), and deceleration zones. Improved navigation, landing, and metering systems would be required and a dynamic airfield sectorization and lighting system might also be needed. Reductions in runway occupancy time in the order of 20 seconds could be obtained, and large gains in capacity would also result.

Integrated Landing Management. This package recognizes the direct relationship between aircraft distance separation on approach, approach speed, time headway over the runway threshold, and runway occupancy time. Sophisticated on-line analysis tools and display systems are used to identify and indicate the optimal path for individual aircraft in order to maximize runway capacity. Aircraft are separated based on time headways and aircraft are sequenced according to their landing characteristics. Increases in capacity of up to 40% could be obtained from this technique.

Findings

Runway occupancy can severely constrain runway capacity today and is likely to provide a more severe constraint in the future as air traffic control improvements are implemented to achieve gains in runway capacity. A large number of factors affect runway occupancy time and further data analysis is needed before some of the items discussed in this study can be implemented.

There are a large number of potential innovations and they can be grouped into six packages of promising innovations. Each of these innovations requires some research, engineering, and development prior to implementation. Reductions of up to 30 seconds can be achieved in runway occupancy time and gains in capacity of up to 40 or 50%.

1. INTRODUCTION

This study is concerned with measures to increase airfield capacity by changing the time spent on the runway by arriving and departing aircraft. The hourly capacity of one or more runways may be limited by factors other than the time each aircraft spends occupying the runway. In this case, reducing runway occupancy time will not achieve an increase in capacity. However, there is ample evidence that runway occupancy time is the limiting factor in determining runway capacity in some circumstances. In addition, changes now being considered in both the air traffic control system and in future aircraft technology (particularly for short-haul aircraft) may relieve some of the other constraints on runway capacity and may offer the opportunity to reduce existing runway occupancy times.

The goal of this study is to identify measures that may be employed to change runway occupancy characteristics, and evaluate the potential gains in runway capacity that they offer, and to make a preliminary assessment of the benefits, costs, and other impacts associated with the implementation of the measures. The results of this study show which measures appear to offer most promise for providing a significant gain in runway capacity at reasonable cost, and identify the associated need for new technology. The study has not attempted to produce detailed estimates of the costs of implementing particular measures, nor of developing detailed assessments of other impacts. The analysis performed in this study has allowed the requirements for these further cost and impact studies to be clearly defined.

In considering the effect of runway occupancy time on capacity, there has been a tendency in the past to concentrate only on the runway occupancy of landing aircraft. However, the runway system is used by both departing and arriving aircraft, and time released by reducing departing occupancy times can in principle be made available to landing aircraft. This study has therefore considered measures to change both departing and arriving occupancy characteristics.

THE NEED FOR INCREASED RUNWAY CAPACITY

As increasing air traffic at an airport begins to approach airfield capacity, delays to aircraft using the airport rise rapidly. The nature of this phenomenon is well understood, and is incorporated in existing procedures for assessing airfield capacity and delay [U.S. Federal Aviation Administration: 1976]. Traditionally, the provision of additional capacity to handle the continuing growth of air traffic has been achieved by building more airports or adding new runways to existing airports. More recently however, widespread public opposition to constructing new airports or even new runways has led to a need to increase capacity of existing facilities.

Since the introduction of wide-body aircraft, the growth in air travel has been accommodated largely by the increased average size of aircraft. At many major airports, aircraft movements have declined while air passenger traffic has increased. While runway capacity was formerly considered synonymous with airport capacity, the focus of recent concern over capacity and congestion has shifted from the airside toward the landside. However, there are good reasons to expect runway capacity to reemerge as a major problem if air traffic continues to grow as forecast.

One reason is that the shift toward increased use of larger aircraft by the trunk carriers cannot continue indefinitely. As the percentage of wide-body aircraft in the fleet increases, the potential for replacing narrow-body equipment decreases. Indeed the next generation of new aircraft (e.g. DC-9-80, B-757, and B-767) provides less seating capacity per aircraft than the last major additions to the fleet. While the possibility exists for a stretched B-747 type aircraft carrying 1,000 passengers, there are few markets that could support such a service at present, and therefore its effect on average aircraft size is likely to be small. When flight crew costs were the major component of aircraft direct operating costs, the economies of scale presented by larger aircraft were an important factor in the increased use of wide-body equipment. As fuel costs tend to replace crew costs as the major components of direct operating cost, the advantage of using larger aircraft is reduced, particularly since the newest generation of aircraft will be significantly more fuel efficient than even the wide-body equipment.

A second reason is the growing role of commuter airlines in providing feeder service to small communities, as a consequence of the Airline Deregulation Act of 1978. This growth of the commuter market influences airport operations in three ways. First, the commuter carriers tend to use small aircraft, thereby reducing average aircraft size, and requiring more aircraft operations to serve a particular passenger demand. The increase in service frequency thereby provided is one of the attractions of commuter airline service and may generate additional traffic when compared with former airline service with regular equipment. Second, these smaller aircraft have very different performance characteristics from large aircraft (being more vulnerable to wake vortex turbulence and tending to fly slower) and require much larger separations on approach, with consequent loss of runway capacity. Third, the market and route structure of commuter airlines is often very different from other carriers that formerly served the same markets. Because of the size of the aircraft, many smaller communities can be served that were not served previously. Small aircraft size favors point-to-point service over multi-stop service, leading to a hub-and-spoke pattern based on major airports. This increases the amount of connecting traffic moving through major airports. Because commuter airlines provide feeder service to longer haul flights at major airports, any attempt to increase effective runway capacity by diverting commuter airline flights to other airports is likely to be strongly resisted.

A third reason to expect a growing problem with runway capacity is the emergence of deeply discounted fares in major markets that are dense enough to support very high volumes of traffic. Much of the recent growth in air travel has been newly generated traffic in these low fare markets. If these pricing practices continue, a large part of the future growth in traffic will occur in those markets, and hence at those airports, that are already carrying the densest traffic.

These three reasons all suggest that future growth in air traffic will occur mainly at the major airports. These are already the closest to saturation and many are experiencing periods of runway congestion. Any significant increase in traffic is likely to lead to a major runway congestion problem with consequent delays. Given the difficulties of providing additional airports in those metropolitan areas, and the growing rather than declining importance of those hubs in the airline route structure, it appears that a pressing need for increased runway capacity will emerge at those airports.

THE MAGNITUDE AND COST OF AIRSIDE DELAY

Notwithstanding prevailing concerns over landside capacity and the fairly stable level of aircraft movements over the past few years, airside delays arising from current levels of congestion are not insignificant, and worthy of major efforts to reduce them. Airport Improvement Task Force studies of the top ten U.S. airports, sponsored by the Federal Aviation Administration (FAA), have found average delays over the year of between one and eight minutes per aircraft, while delays to individual aircraft can be over an hour. It has has been estimated that delays to aircraft in the U.S. due to airport congestion cost the airlines over $1 billion in 1980.

In interpreting these data, it should be noted that the cost estimates refer only to those costs incurred by the airlines as a consequence of delay. The general approach is to multiply the total delay in hours per year by the average hourly operating cost of the aircraft. While an estimate of the minutes of actual delay incurred by each flight can be made, obtaining a cost for that delay is considerably more difficult. Apart from the usual problem in such studies of whether delay is additive, or in other words whether a delay to one aircraft of thirty minutes is the same as a two minute delay to each of fifteen aircraft, there is also the question of whether the marginal and average hourly aircraft operating costs are the same. In any event, the procedure ignores the cost of any inconvenience to the passenger arising from aircraft delays, other than that for which the airlines provide compensation. If these costs are added in, the resulting cost of airside delay is likely to greatly exceed $1 billion.

The largest delays occur in Instrument Flight Rules (IFR) weather. Runway capacity is limited by safety concerns that translate into separation standards that essentially eliminate collision risk. In IFR weather, when aircraft cannot see each other and cannot be seen by the tower controllers, more stringent separation standards and air traffic control (ATC) procedures are applied, reducing runway capacity and thus increasing the delays incurred by a given level of traffic.

THE ROLE OF RUNWAY OCCUPANCY AND OTHER FACTORS IN RUNWAY CAPACITY

Hourly runway capacity is defined as the maximum number of aircraft operations that can use a runway or a system of runways in an hour under specified operating conditions. An operation is an arrival or a departure.

Runway capacity (C) is the inverse of the minimum time interval or headway consistently achievable in saturated conditions (H), i.e:

$$C = \frac{1}{H}$$

where time intervals between aircraft (headways) are measured at the runway threshold. For arrivals, time intervals are measured from the time that the aircraft crosses the runway threshold. For departures, intervals are measured from the time that the aircraft starts its take-off roll on the runway.

H depends on required separations between aircraft in the air and on the runway, and on aircraft speeds. Because individual values of headway vary (due to fluctuations in operating conditions, etc.), H is a weighted average value that reflects the occurrence of different individual values of headway.

For example, a runway may be used by a stream of narrow-body arrivals (e.g. B-727, DC-9). The minimum separation required between these aircraft in the air may be 3 miles, and they may travel at a ground speed of 120 knots. In this situation the minimum headway required is 90 seconds. In practice, controllers tend to add a "buffer" to the minimum headway to produce an average headway which can be regarded as the minimum headway consistently achievable under saturation conditions (H). In this example, we will let the buffer be 30 seconds and therefore H is 120 seconds. (In reality, actual headways between individual pairs of aircraft vary about the average and may be as low as 80 seconds or as high as 160 seconds.) In this situation the runway capacity (C) is 30 aircraft per hour.

The above example is simpler than often occurs in the real world because of (a) the influence of runway occupancy, (b) arrivals and departures using the same runway, (c) a mix of different types of aircraft, and (d) other operating conditions.

The above example can be extended to include runway occupancy. The aircraft may have a normal runway occupancy time of 50 seconds, and controllers may add a buffer of 20 seconds when making control judgments. In this situation a minimum headway of 70 seconds would be required between aircraft to account for runway occupancy.

Note that in this example the 3 mile air separation requirement (90 second headway) constrains capacity while runway occupancy (70 second headway) does not. In cases with mixed operations (arrivals and departures using the runway), runway occupancy would constrain capacity rather than air separation. Runway occupancy would also constrain capacity for an arrivals-only runway if the air separation requirement were reduced in the future.

A list of the factors that influence runway capacity is given in Table 1.1, divided into six general categories. Each of these categories is discussed below.

Airfield characteristics. The airfield layout includes the number, length, width, orientation of, and the separation between, runways, taxiways (including runway exits), and the apron and aircraft parking areas. In general, an airfield with more and/or larger facilities has a larger capacity than an airfield with fewer and/or smaller facilities.

Some exceptions and limits to this generalization exist, particularly when airfield components interact with each other. Weather conditions, pavement maintenance, noise, and other factors often cause some runways to be out of use. The number and direction of runways in use, and whether or not arrivals and/or departures are accommodated on each runway, will affect runway capacity. Landing aids, both instrument (e.g. ILS) and visual (e.g. runway lights), can permit aircraft to make

Table 1.1

Factors Influencing Runway Capacity

Airfield Characteristics	Airfield Layout Runways in use Landing and Navaids
Aircraft Demand	Mix of Aircraft Types Ratio of Arrivals to Departures
Aircraft Operating Characteristics	Approach Speed Landing Profile Deceleration on Runway Exit Maneuvering Wake Turbulence
ATC Equipment and Procedures	Radar Separations on Runway Separations in the Air Metering and Sequencing
Weather Environment	Ceiling and Visibility Wind Precipitation Temperature and Pressure
Constraints	Noise Airspace Runway Length and Strength

full use of a runway system, as can navaids (e.g. VORTAC).

Aircraft demand. The mix of different aircraft types using a runway system will influence capacity because of different aircraft operating characteristics and ATC procedures that apply. The ratio of arrivals to departures is also important because these two types of operation have different separation requirements.

Aircraft operating characteristics. Each type of aircraft and each individual aircraft exhibit different aircraft performance from day to day because of variations in aircraft operating characteristics and pilot technique. Approach speeds may vary because of different aircraft weight or wind velocity, and the landing profile may vary depending on pilot technique. Deceleration on the runway is influenced by surface conditions (braking action), reverse thrust and braking capabilities, and pilot technique. The maneuver to exit from the runway depends on aircraft size and turn characteristics in addition to exit design and pilot technique. Wake turbulence produced by an aircraft and the susceptibility of following aircraft to this wake also influence runway capacity.

ATC equipment and procedures. The availability of radar permits aircraft to be safely separated at distances less than would otherwise be feasible. Separations between aircraft on the runway and in the air are influenced by minimum separation requirements identified in FAA Handbooks. Systems used to organize a smooth flow of aircraft to a runway (metering and sequencing systems) will also affect the actual aircraft separations achieved and hence runway capacity.

Weather environment. Low cloud ceiling and/or visibility influence capacity: directly, by limiting the ability of aircraft to land on runways; and indirectly, by causing air traffic controllers to use larger separations between aircraft. Headwind slows aircraft down and crosswind makes landings more difficult, and both of these factors can limit capacity. Precipitation can result in reduced tire-pavement friction, thereby limiting the deceleration that can be achieved by braking or by use of reverse thrust (due to pilot concerns about aircraft stability in crosswinds). Temperature and pressure can influence runway length requirements and approach and departure speed, thereby impacting capacity indirectly.

Operating constraints. A number of constraints can reduce capacity to lower levels than could be achieved without these constraints. Limits on aircraft noise can reduce or eliminate the feasibility of certain runway uses and/or ATC procedures. Airspace constraints (due to adjacent airports, topography, restricted areas, etc.) can also eliminate certain runway uses and/or ATC procedures. Runway length and strength constraints can mean that certain aircraft cannot use particular runways.

Many of the factors listed in Table 1.1 influence capacity in part by influencing runway occupancy time. When runway occupancy time constrains runway capacity, the constraint reflects both the mean occupancy time and the variations around the mean (i.e. uncertainty about the actual value of runway occupancy time for a specific aircraft).

Both the mean and the variation of runway occupancy time are profoundly influenced by the exit selected by a pilot to leave the runway. In general, lower mean runway occupancy times occur when pilots select exits closer to the runway threshold. Larger variations in runway occupancy time occur when conditions cause some pilots to select one exit while other pilots select different exits. Exit selection is a complicated process performed by the pilot based on numerous variables, including many of those listed in Table 1.1.

Efforts to reduce runway occupancy time must therefore include the provision of appropriate exits and assistance to pilots in selecting the exit that will safely minimize runway occupancy time for the specific conditions prevailing.

IMPLICATIONS OF FUTURE TRENDS IN THE ATC SYSTEM

The National Aeronautics and Space Administration, FAA, and others are conducting an extensive research, engineering, and development (R,E&D) program that is designed to improve the ATC system. The goals of the R,E&D program are oriented (1) to provide safe and efficient service for the higher levels of aviation demand that are predicted for the future, and (2) to make gains in productivity and reduce controller workload.

One of the objectives of the program is to achieve reductions in separations between aircraft and consequent increases in runway capacity. For example the program may result in reductions in:

- The minimum longitudinal separation between aircraft on the final approach course; from three miles today to either two and one half or two miles in the future.

- The minimum lateral separation between aircraft conducting simultaneous independent approaches to parallel runways; from 4300 feet today to as low as 2500 feet in the future.

- The minimum separation between aircraft conducting dependent final approaches to parallel or converging runways may also be reduced.

Each of these reductions in separation would enable more aircraft per hour to approach runways in IFR weather conditions. In this situation, runway occupancy time would become an even more important influence on runway capacity than it is today.

Various elements of the R,E&D program offer the potential for new equipment and procedures that may assist in managing runway occupancy more effectively in the future.

One element of the program aims to increase the capability for all-weather operations; including reduced weather minima for approach, landing, roll-out, and taxiing off the runway. The improved guidance systems and positive indication of a clear runway that are required for all-weather operations are being investigated by FAA.

Another element of the program addresses the potential for increased pilot involvement in ATC functions. Cockpit display of traffic information would permit the pilot to make direct judgments concerning the availability of a runway for landing.

A third element of the program relates to increased accuracy of four-dimensional navigation. Microwave landing systems and satellite based navigation systems offer the potential for improved position accuracy, while integrated ATC flow management and improved aircraft flight management systems offer the potential for improved timing of approaches. Automated data links offer the potential for rapid interchange of data between an aircraft and the ground or other aircraft. Each of these items contributes to improved four-dimensional accuracy which could be extended from the approach phase to the landing and roll-out phase.

A fourth element of the program includes techniques to improve the monitoring and control of aircraft on the airport surface. Improved ground surveillance radar and alphanumeric displays would offer the potential for improved verification of runway occupancy and clearance.

In summary, future trends in the ATC system imply that (1) runway occupancy will become more critical in the future than it is today, and (2) that technology will be available to assist in refining runway occupancy. The challenge is to find ways to adapt and use the developing technology to provide benefits in the area of runway occupancy.

IMPLICATIONS OF NEW AIRCRAFT TECHNOLOGY

A considerable research and development program is currently being conducted by NASA and others to develop the necessary technology for advanced short-haul aircraft. The need for new technology arises out of the recognition that many existing conventional air carrier aircraft are designed to operate most economically over longer stage lengths than those usually associated with short-haul operations. At the same time, the development of an entirely new type of aircraft, configured expressly for a short-haul mission and utilizing the most advanced technology available, presents an opportunity to design an aircraft with performance characteristics on the runway and in the terminal airspace that will enable it to utilize short runways, thereby permitting expanded operations at busy airports.

The characteristics of an advanced technology short-haul aircraft are likely to include

- relatively short take-off and landing distances
- steep climb and descent profile potential
- improved low-speed handling for maneuvering in the terminal airspace
- relatively low approach and climb speeds
- improved instrumentation and approach aids.

The development of new aircraft presents opportunities to include special features that would enable a higher runway capacity to be achieved. It also points out the need to examine the interaction of advanced short-haul and conventional aircraft when operating in mixed streams, and the impact of advanced short-haul aircraft operating separately from the conventional aircraft stream within the existing airspace and airfield. These interactions and impacts may impose restrictions on the operation of conventional aircraft by limiting their ability to fully utilize new measures designed to reduce runway occupancy time. For example, a parallel short runway with triple arrival streams may limit aircraft separations on the approach paths to the other runways, or traffic crossing from a separate short-haul runway may reduce the capacity of a conventional runway. These limitations would tend to offset the capacity increases that the new technology offers.

Consideration of the impacts of advanced short-haul aircraft technology should include both the performance characteristics of the new aircraft and the consequences of dedicated airspace and airport areas for separate short-haul operations.

OBJECTIVES OF THIS STUDY

The overall goal of the research was to identify and assess potential improvements that may reduce the impact of runway occupancy on airport congestion, today and in the future.

Specifically, the following four objectives for the research were identified:

1. Develop a thorough understanding of the factors that affect runway occupancy, and the extent of their effect.

2. Identify potential innovations that appear promising in terms of their effectiveness in meeting the objective of reducing the impacts of runway occupancy on airport congestion.

3. Design a research program to assess in depth the impacts of the promising potential innovations, and to determine the requirements for their implementation.

4. Assess the impact of technology developments in the areas of advanced short-haul aircraft and air traffic control measures on runway occupancy.

Factors affecting the approach and landing process may be classified into five general categories:

1. Aircraft
2. Airport
3. Pilot
4. Air Traffic Control
5. Environment.

Within each of these categories, there are many individual factors that influence the approach and landing process. For example, factors in the aircraft category include aircraft type, landing configuration, landing weight, and instrumentation. One objective of the research was to gain a better understanding of the relative importance of these factors in determining runway occupancy time.

Potential innovations were identified, described, and assessed to establish (1) the benefits that might be obtained, (2) the requirements for implementation, and (3) the side effects resulting from implementation. Results of the assessment were used to assist in identifying the more promising innovations.

The definition of a research program required to further analyze potential innovations or to move the innovations towards practical implementation was an important component of the study. In particular, such a research program would include any data acquisition needed to complement available relevant data and permit a thorough evaluation of promising innovations.

The potential contribution of advanced technology short-haul aircraft on runway occupancy was also assessed, together with identification of areas of further modification to this technology to support runway occupancy reduction objectives. Investigation of potential innovations included consideration of the requirement for, and contribution of, new technology in air traffic control equipment development.

Scope of the Research.

The research was exploratory in nature and its main objective was to identify and assess potential innovations. The research scope encompassed the necessary analysis to address the two classes of questions identified earlier: airport and air traffic control questions of particular interest to the FAA, and aircraft technology questions of particular interest to NASA. To accomplish research objectives within limited resources, the scope has been specifically limited in certain areas.

One limitation was that no additional data acquisition be undertaken during the research. Data needs, over and above those data which already exist, have been identified as part of a follow-on research program aimed at further assessment of promising innovations. Another limitation to the scope was a focus on air carrier operations. General aviation aircraft have runway operating characteristics that are typically significantly different from air carrier aircraft and often have significantly lower runway occupancy times. While it is possible that developments in advanced short-haul aircraft technology may create more of a continuum between air carrier and general aviation aircraft, the empirical investigations in this research have focussed only on air carrier operations.

In identifying potential innovations, no a priori limitations were placed on scope. The research sought to identify as complete a set as possible of potential innovations that may require changes to the aircraft, airport, pilot procedures, and air traffic control system. Even potential innovations that appeared on first glance to be unrealistic or infeasible were only excluded after some assessment. Increased realism was introduced as some innovations were eliminated and the more promising ones identified and subjected to further assessment. In making assessments of the potential innovations, the scope was sufficiently wide to address, at least in a preliminary manner, all impacts including technical, economic, operational, safety, environmental, energy, political, and institutional impacts. A broad scope at this early stage ensured that the most promising innovations were identified.

As part of the analyses involving the factors that determine runway occupancy time, models of the aircraft landing process were developed, and extensive use was made of the FAA runway capacity models.

Research Plan.

The plan for the conduct of the research focused on five major activities that are tied directly to the objectives of the research.

1. Assessment of available data. This step consisted of preparing an inventory of data sources and then acquiring selected data on runway operations and occupancy time. The data acquired was reduced as necessary and analyzed with two purposes in mind. The first was to assess the accuracy and suitability of the data for purposes of this research. The second was to extract from the data information

needed to infer the impacts of the various factors that affect runway occupancy time.

2. Identification of significant factors. Analysis of the data was performed to identify the factors that appear to have an effect on runway occupancy time and to quantify their effects.

3. Identification of potential innovations. This activity consisted of a complete and unrestricted identification of all potential innovations that could be used to reduce runway occupancy mainly by acting on the factors that appear significant in influencing runway occupancy times.

4. Assessment of innovations. A set of performance evaluation criteria were identified and related to the objective of reducing runway occupancy. These criteria included implementation costs, financing, environmental, energy resource, safety, political, and institutional aspects, and measures of an innovation's impact on capacity, delay, and operating costs. The criteria were applied to the innovations in an evaluation process. The result of this process was a coherent set of packages of innovations that are deemed worthy of additional investigation and potentially promising for implementation.

5. Implementation requirements. The research concluded with a definition of the implementation requirements of the promising innovations in terms of the additional studies and evaluations needed.

These five activities are described in more detail in the following four chapters. Chapter 2 describes the current situation regarding the influence of runway occupancy time on capacity, documents the previous studies that have been performed addressing the runway occupancy behavior of air carrier aircraft, as well as the data sources identified in the course of the research, and summarizes the effect of the factors that were found to influence runway occupancy time. Chapter 3 describes the identification and preliminary evaluation of potential innovations to reduce runway occupancy time. The more promising innovations were then grouped into six packages which are described and evaluated in Chapter 4. Chapter 5 summarizes the findings of the study and identifies the further research required to move the innovation packages toward implementation.

2. THE CURRENT SITUATION CONCERNING RUNWAY OCCUPANCY

The search for ways to reduce the runway occupancy time of landing aircraft is not just a recent concern, but has been the subject of considerable attention in the past. Indeed, the more general concern over the saturation of airside capacity at major airports following the introduction of the jet transport aircraft and growth of air travel in the early sixties led to studies of runway occupancy that resulted in the current design criteria for exit taxiway geometry and location. The introduction of the wide-body aircraft, and the subsequent shift in congestion from the airside towards the landside, reduced some of the pressures on runway capacity, while increased separation requirements necessitated by wake turbulence from large aircraft shifted attention away from runway occupancy time as a constraint on capacity. As a consequence, the pace of research on runway occupancy problems slowed considerably. However, with the recently renewed interest in runway capacity, a number of studies have been performed that collected valuable data on the operation of the runway system.

This chapter examines the current state of knowledge about both runway occupancy and the factors affecting it. Runway occupancy is important because it affects runway capacity, and therefore this chapter begins with an examination of the influence of runway occupancy time on capacity. This examination is followed by a review of previous studies of runway occupancy, and data sources on the performance of aircraft on the runway system. Finally, based on analysis of these data and previous work, the primary factors affecting runway occupancy time are identified and discussed.

THE INFLUENCE OF RUNWAY OCCUPANCY TIME ON CAPACITY

As indicated in the previous chapter, runway occupancy time can have different levels of impact on runway capacity, depending on the specific situation. In some situations, required separations between aircraft in the air are sufficiently large that they determine capacity directly, and runway occupancy does not influence capacity. In other situations, required separations between aircraft in the air do not affect capacity significantly, and there is an inverse relationship between runway occupancy time and capacity.

For example, in IFR weather conditions and with today's ATC rules, the capacity of a runway which is used for arrivals only is not normally influenced by runway occupancy. However, if the runway were used by arrivals and departures, then runway occupancy is a major factor in capacity.

Typical values of arrival runway occupancy time of large jet transport aircraft (e.g. B727) are in the range 45 to 65 seconds. Typical required separations between these aircraft in the air are 3 to 4 miles, which translates to a headway of approximately 85 to 110 seconds. Typical values of departure runway occupancy time are in the range 35 to 50 seconds.

Figures 2.1 and 2.2 illustrate the influence of runway occupancy time on IFR hourly runway capacity for several different situations. Figure 2.1 presents data for a runway used only by arrivals (100% arrivals), while Figure 2.2 presents data for a runway used equally by arrivals and departures (50% arrivals). Two sets of curves are shown on

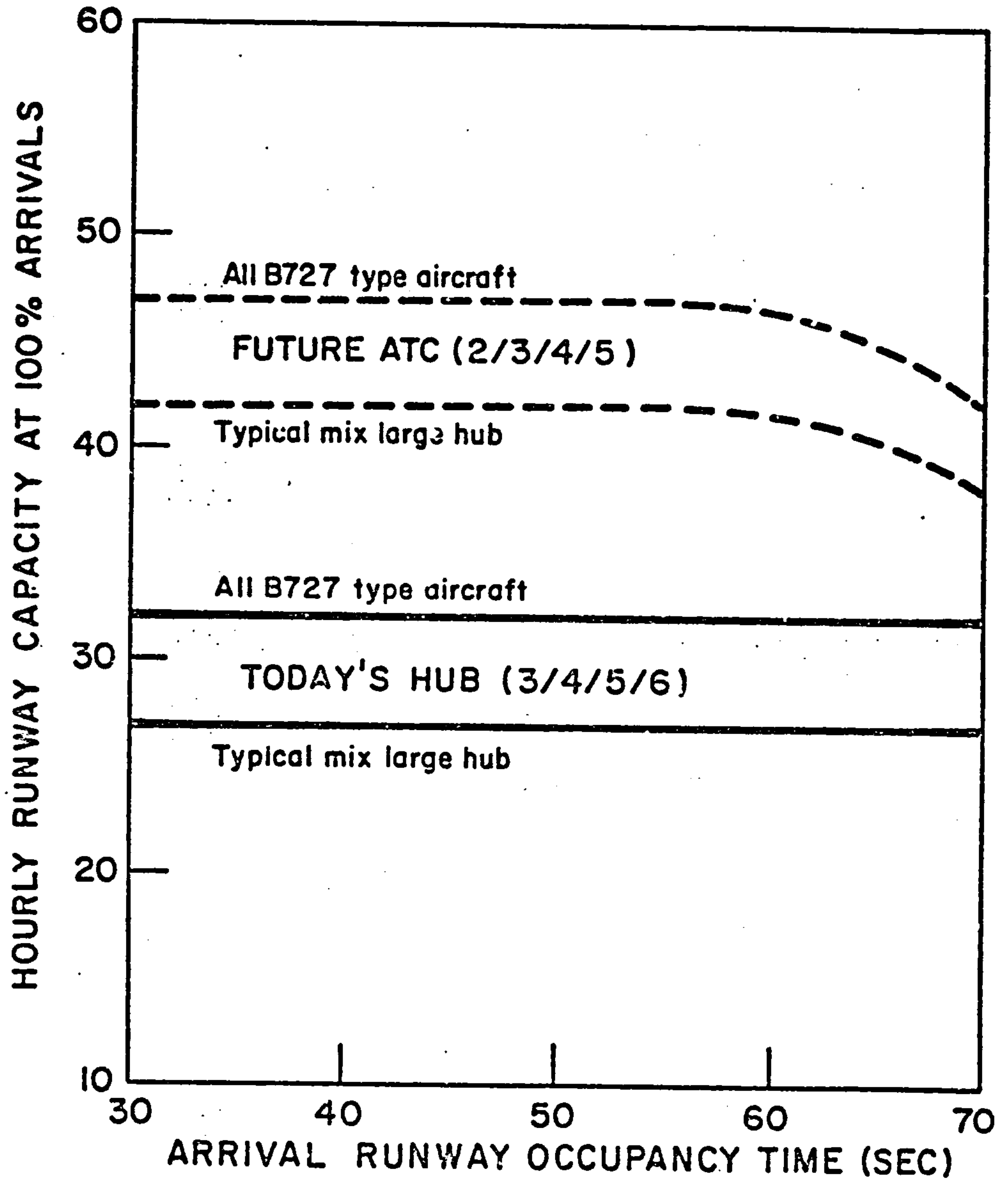


FIG. 2.1 Influence of Runway Occupancy Time on IFR Capacity--Landings Only.

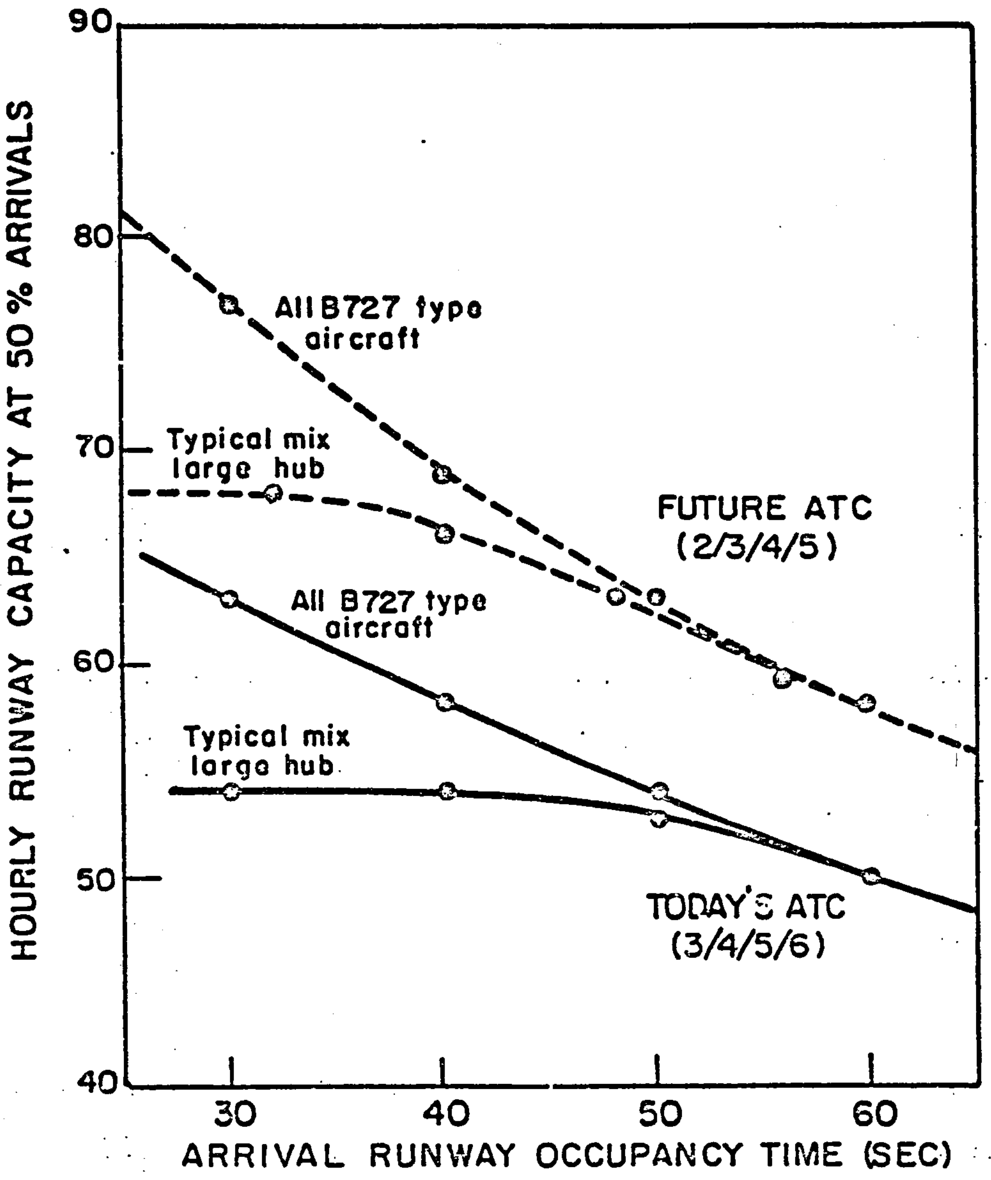


FIG. 2.2 Influence of Runway Occupancy Time on IFR Capacity--Mixed Operations.

each figure, one set relating to today's ATC rules (with a minimum separation of 3 miles in IFR conditions) and the second set of curves relating to one alternative potential future ATC rule (with a minimum separation of 2 miles). The impact of two alternative aircraft mixes are also presented: the first mix contains only B-727 type aircraft, while the second mix is representative of mixes encountered at large hub airports (with approximately 15% heavy jets and 10% small aircraft).

The graphs demonstrate that when arrival runway occupancy time is large, it can directly influence capacity, and that when runway occupancy is small its influence on capacity is often masked by other influences (e.g. required separation in the air, or departure runway occupancy time).

Changes in runway occupancy time can cause different impacts on runway capacity, delays to aircraft, and aircraft operating cost, depending on the specific operating conditions. For the baseline situation discussed in this report (two independent parallel runways, typical mix at large hub airports, etc.) a 20 percent reduction in runway occupancy time would cause approximately 6 to 10 percent increase in runway capacity. For an airport operating with a demand close to capacity, this might achieve a 20 percent reduction in delays to aircraft in the peak hour. When averaged over the year, these delay savings might be of the order of $75 million per year at the nation's busiest 25 airports. These values are order-of-magnitude estimates only and should be refined as specific innovations are considered for implementation.

The amount of benefits obtainable from a reduction in runway occupancy time depends on the prevailing operating conditions. For example, the benefits are greater with a stream of B-727 type aircraft than with the typical mix of traffic at large hub airports. The following tabulation identifies several different factors and their general effect on the significance of benefits to be obtained from reductions in runway occupancy time:

Factor	More Benefits	Less Benefits
Aircraft mix	All B727 type aircraft	Typical mix, large hub
Percent arrivals	Equal amount arrivals, departures	All arrivals
ATC system	Future-reduced separation	Today's system
Demand	High	Low

DEFINITION OF RUNWAY OCCUPANCY

The rules governing runway occupancy are defined by FAA. These FAA rules require specific minimum separations between aircraft using a runway. Different rules apply for arrivals and departures and for different categories of aircraft. In addition, certain deviations may be permitted.

Arrival Aircraft Runway Separations. An arriving aircraft must be separated from a previous aircraft using the same runway by ensuring that the aircraft does not cross the landing threshold until the previous aircraft has either landed and taxied off the runway (if the previous aircraft is an arrival) or departed and crossed the runway end (if the previous aircraft is a departure). The precise language is given in Appendix A, Paragraph 1120. (Appendix A is extracted from FAA Order "Air

Traffic Control" 7110.65B, Change 4, 1/1/81.)

Certain additional rules are specified by FAA which modify this definition to permit a second aircraft to use the runway before the first aircraft has cleared the runway. Examples of these variations are given in Appendix A, Paragraphs 1120 and 1121 for land based aircraft, and Paragraph 1522 for sea lane operations. Note that the rules are different for Categories I, II, and III aircraft. (Category I aircraft are lightweight single engine personal type propeller driven aircraft. Category II aircraft are lightweight twin engine propeller driven aircraft weighing 12,500 lbs. or less. Category III aircraft are all other aircraft.)

Departure Aircraft Runway Separations. A departing aircraft must be separated from a previous aircraft using the same runway by ensuring that the aircraft does not begin take-off roll until the previous aircraft has either landed and taxied off the runway (if the previous aircraft is an arrival) or departed and crossed the runway end (if the previous aircraft is a departure). The precise language is given in Appendix A, Paragraph 1110.

As in the arrival case, certain additional rules are specified by FAA which modify the definition of departure runway separation requirement to permit a second aircraft to use the runway before the first aircraft has departed and crossed the runway end. Examples of these variations are given in Appendix A for land-based aircraft and sea lane operations.

Procedural Deviations. Further deviations may also be permitted from these rules to cover exceptional or unusual requirements. Examples of these deviations are given in Appendix A, Paragraph 11.

For military operations, a flight of aircraft may contain two or more aircraft in formation. These are considered to be a single aircraft operation as far as air traffic control is concerned. Therefore, all aircraft belonging to a flight may be on the runway at the same time.

Major USAF Air Commands define their own procedures for required separations between aircraft on the runway that belong to different flights. For example, some USAF Commands require only 4000 ft. between tactical aircraft landing on the runway between sunrise and sunset.

Rationale for Required Separations on the Runway. Required separations between aircraft are designed to avoid collisions between the aircraft while they are on a runway. The various required separations appear to have evolved over time in response to concerns about safety, capacity, and the different characteristics of aircraft.

Special and more rigorous requirements apply to group III civil arrival aircraft when compared with all other types of aircraft (i.e. groups I and II aircraft, military aircraft, and departures). Only group III civil arrival aircraft are required to completely leave the runway before another aircraft crosses the runway threshold (or rolls on takeoff). In other cases, more than one aircraft are permitted on the runway at the same time. The rationale for the special treatment of group III civil arrival aircraft is not clear, but it may be related to the lack of maneuverability of these aircraft and/or the potential severity of any accident involving these aircraft. It is not clear that the current definition of required runway separation for group III civil arrival aircraft provides the optimum tradeoff between safety requirements and runway capacity.

No written documentation is currently available from FAA that explains the rationale for the rules, and in fact other FAA rules appear to imply that the runway separation requirements for group III civil arrival aircraft may be overly conservative.

For example, Appendix A, Paragraph 1121, gives required separations for operations on intersecting runways. Aircraft arrival operations on one runway can take place simultaneously with operations on an intersecting runway as long as instructions are issued to restrict one aircraft from entering the intersecting runway to be used by another aircraft. The distance required between the landing threshold and an intersecting runway in order that an aircraft can stop short is given in FAA Order "Facility Operation and Administration" 7210.3E Change 5, 10/9/80. Appendix B, Paragraph 1227, extracted from this order, shows that the distance depends on airport elevation and aircraft group. Definition of aircraft groups is contained in Appendix 3 to FAA Order 7110.65B which is reproduced as Appendix C to this report. A summary of selected aircraft types and stop-short distances at an airport with less that 1000 feet elevation is given in Table 2.1.

Table 2.1 shows that most large jets (e.g. B727, B737, DC9) can stop short of an intersecting runway 6,000 feet from the landing threshold and that most heavy jets (e.g. A300, B707, B767, L101, DC8, DC10) can stop short in 8,000 feet. (In addition, many of these heavy jets

Table 2.1

Selected Arrival Aircraft Stop-Short Distance Requirements

Distance	Aircraft Group	Aircraft Type
2,000	2	DH7
4,500	3	FA27 DC3 N265
6,000	4	B727 B737 HS748 LR25 G2 L188 DC9
8,000	5	CONC A300 B707 B745 B767 L101 DC8 DC10
8,400	5A	B747

Source: FAA Orders 7110.65B and 7210.3E

regularly land on runways that are 7,000 feet or less in length, e.g. LaGuardia Airport.) Based on this data, it could be argued that aircraft that can stop short of other runways can also:

a) Use a specified exit from the runway, located at or beyond the stop-short distance, or

b) Stop on the runway by the stop-short distance, thereby avoiding another aircraft that stopped on the runway beyond the stop-short distance.

Incorporation of this rationale into FAA rules could permit significant increases in runway capacity by reducing runway separation requirements.

Figure 2.3 shows an arrival aircraft deceleration profile for a B727-200 taking an exit 6800 feet down Runway 26 at Atlanta. This aircraft took 42 seconds to reach 6000 feet and 56 seconds to reach the exit at 6800 feet. If the runway separation required were modified to permit a similar aircraft to use the runway when the first aircraft crossed the 6000 feet point, 14 seconds time separation (25% of today's runway occupancy time) might be saved in this case.

An argument against this modification to runway separation requirements might be based on safety grounds. The most critical situation appears to occur when both the lead and trailing arrivals suffer specific emergencies that cause the following actions:

1. The lead aircraft decelerates quickly on the runway and stops on the runway short of the 6000 foot point.

2. The second aircraft either (a) executes a missed approach or (b) does not decelerate as rapidly as the first aircraft.

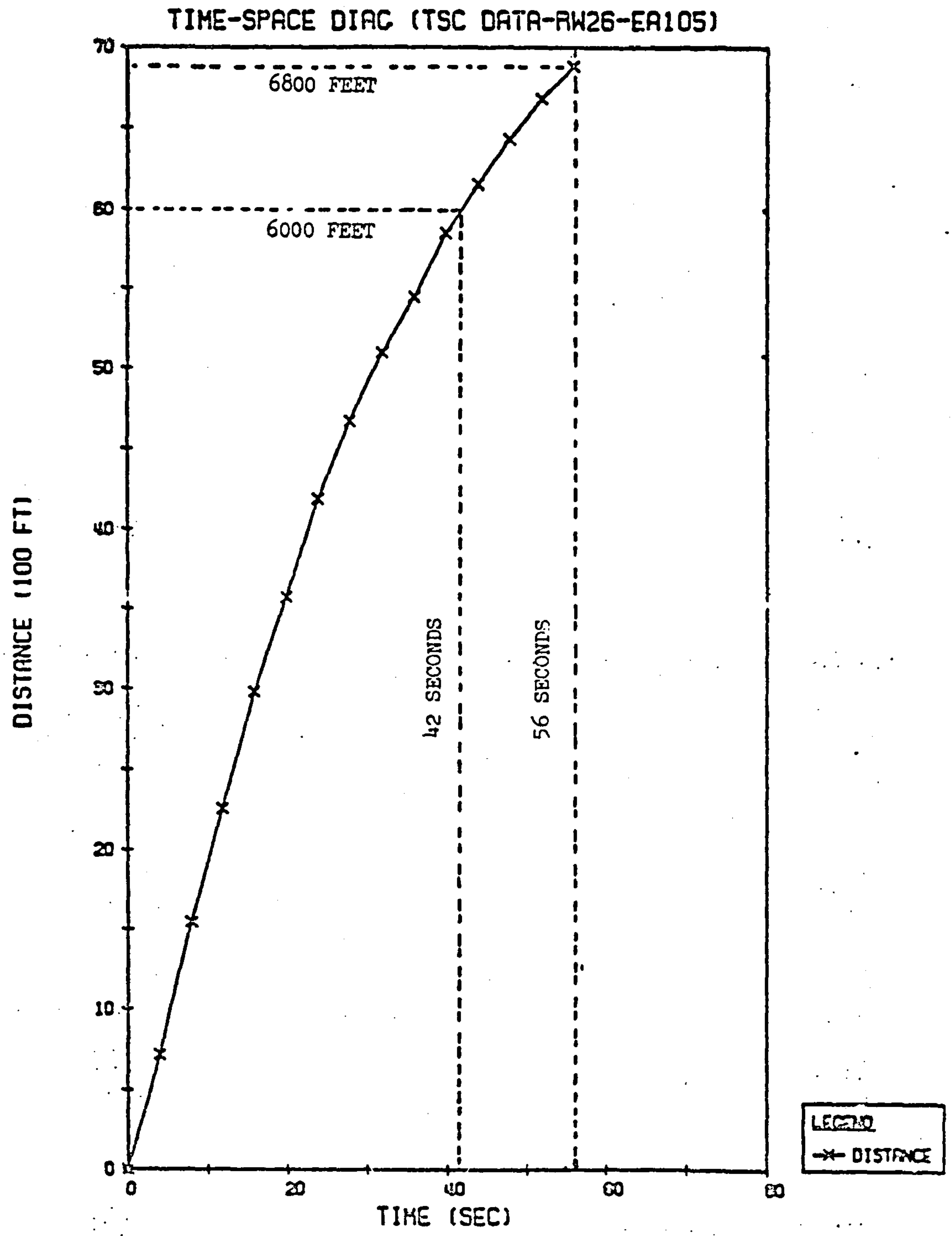


FIG. 2.3 Aircraft Deceleration Profile for B-727-200--
Atlanta Runway 26.

In practice, even this unlikely situation would probably not result in a collision. For example, if the first aircraft decelerates very rapidly (at say 8 feet per second per second, twice the normal rate) from a short touchdown point (750 feet, half the normal distance); it will stop 31 seconds after crossing the threshold at a distance of 3775 feet from the threshold. If the two aircraft are separated by 45 seconds (1.6 miles at 130 knots), the first aircraft will come to a stop while the second aircraft is more than half a mile from the runway threshold, at an altitude of more than 200 feet above the runway. It is very likely that the second aircraft will have been alerted concerning the first aircraft's difficulties before the full 31 seconds has passed. However, even if it learns of the problem after 31 seconds, there is still sufficient time available for the second aircraft to make a missed approach or go-around without colliding with the first aircraft (which is stationary at a point 3775 feet from the threshold).

It therefore appears that there is some potential for changing ATC rules concerning runway occupancy to achieve gains in runway capacity without compromising safety significantly.

Need for Review of Runway Occupancy Rules. Given the potential for reduced runway separation requirements for Group III civil aircraft and the uncertainty about the rationale for today's standards, a further examination of runway separation requirements is appropriate. Further theoretical analysis, data collection, aircraft simulator runs, and live field tests under controlled conditions could demonstrate whether reduced runway separation requirements are safe and feasible.

This further work should also examine the rationale for selecting "time across threshold" and "tail of aircraft crosses runway edge" as the basis for runway separation requirements. A series of alternative definitions for the start of runway occupancy is available, for example:

- Time across start of approach lights
- Time across threshold
- Time of touchdown.

It is not clear in advance of detailed analysis why the second of these three definitions is the best definition, given safety and capacity considerations. Time across start of approach lights would give some increased margin for error at the cost of reduced capacity. Time of touchdown would yield capacity gains at the cost of reduced margin for error.

Similarly, a series of alternative definitions for the end of runway occupancy is available, for example:

- Time tail of aircraft clears runway hold line
- Time tail of aircraft clears runway edge
- Time nose of aircraft clears runway edge
- Time aircraft leaves runway center-line for exit.

It is again not clear why the second of these four definitions is the best definition given safety and capacity considerations.

The above discussion illustrates that reductions in arrival runway occupancy time and gains in capacity can be obtained by changing the ATC rules, without altering the way that aircraft perform during landing and roll-out. The following paragraphs discuss the possibility of changing the way that aircraft decelerate without changing the ATC rules. In practice, a combination of ATC rule and aircraft performance changes may be the most effective method of achieving capacity gains.

CHANGES IN AIRCRAFT PERFORMANCE ON THE RUNWAY

Runway occupancy time is determined by the performance of the aircraft from the runway threshold to the exit. Several major events occur during runway occupancy:

1. Aircraft crosses runway threshold
2. Main gear touches down
3. Reverse thrust starts
4. Braking starts
5. Reverse thrust ends
6. Braking ends
7. Exit maneuver starts
8. Aircraft clears runway.

These events do not necessarily occur in the order shown. The sum of the time between these events equals runway occupancy time. The time between any two events is influenced by aircraft performance capabilities, environmental conditions, airfield layout and condition, air traffic control instructions, and pilot technique. The time between events is addressed in the following paragraphs.

<u>Aircraft crosses runway threshold to main gear touches down.</u> When

conducting a precision approach, the pilot normally intends to cross the runway threshold 50 feet above the runway, at a descent rate that corresponds with the glide slope, and at a speed that reflects aircraft weight and wind conditions. At some stage during the descent, approach speed is reduced and a flare is initiated to reduce the descent rate at touchdown. Variations in aircraft performance, environmental conditions, and pilot technique cause the distance and/or time to main gear touchdown to vary from aircraft to aircraft. Typical values of time from threshold to main gear down may range from 6 to 10 seconds. (All times in these paragraphs are approximate and refer to Boeing 727 type aircraft. Note that the times are not necessarily additional because of the overlap of some events.)

Main gear touches down to reverse thrust starts. When the main gear touches down, the spoilers are deployed and lift is essentially eliminated. The nose of the aircraft drops until the nose gear touches down. The pilot mentally confirms that a safe landing can continue and then engages thrust reversers and increases engine speed. Depending on pilot technique, reverse thrust may be initiated before the nose gear touches down. The amount of reverse thrust is selected by the pilot, depending on airfield, environmental, and air traffic conditions. Typical values of time from main gear down to start of reverse thrust may range from 2 to 6 seconds.

Reverse thrust starts to braking starts. Reverse thrust is most effective in deceleration at higher speeds, while braking is most effective at lower speeds. Most pilots use a combination of braking and reverse thrust to maintain a relatively smooth deceleration process.

Braking will tend to start earlier in situations with a dry and/or short runway, with an exit located close to the threshold that minimizes travel time to the gate, and in heavy traffic conditions. Pilot technique is paramount in this process. Typical values of time from start of reverse thrust to start of braking may range from 5 to 20 seconds.

Braking starts to reverse thrust ends. Reverse thrust becomes less effective at lower speeds, and in addition there is the potential for debris to be sucked into the engines. Several airlines require pilots to end reverse thrust at speeds between 60 and 90 knots. Typical values of time from start of braking to end of reverse thrust may range from 5 to 20 seconds.

Reverse thrust ends to braking ends. Braking ends when the pilot is assured that the exit maneuver can take place safely. Safe exit speed depends on exit angle, turn radius, and length of exit, and ranges from 10 to 60 knots. Typical values of time from end of reverse thrust to end of braking may range from 10 to 25 seconds.

Braking ends to exit maneuver starts. The exit maneuver commences when the aircraft leaves the runway centerline to enter the exit. Pilots tend to adjust the deceleration process to essentially complete deceleration by the start of the exit maneuver. Typical values of time from end of braking to start of exit maneuver may range from -5 to +10 seconds.

Exit maneuver starts to aircraft clears runway. The runway is clear when the tail and wing of the aircraft are clear of the runway edge. The time taken to clear the runway depends on exit speed and layout. A longer distance (approximately 700 feet) must be travelled by aircraft to clear a runway by means of a high speed exit than the distance (approximately 350 feet) travelled to clear a runway by a right angled start of exit. Typical values of time from start of exit maneuver to aircraft clearing runway may range from 7 to 20 seconds.

The above paragraphs demonstrate that there are many components and factors that influence runway occupancy time. The impact of varying some of these factors on runway occupancy time was tested by running a computer model that simulates aircraft movement.

The baseline deceleration profile is shown in Figure 2.4. In this hypothetical baseline case, the aircraft crosses the runway threshold at 134 knots, decelerates at 0.75 ft/sec^2 in the air, and the main gear touches down after 7 seconds at 1600 feet from the runway threshold. The nose gear touches down after 10 seconds when the aircraft is travelling at 130 knots. After 28 seconds, the aircraft is 5500 feet down the runway, travelling at 80 knots after decelerating at 4.5 ft/sec2 on the runway. After 49 seconds, the aircraft is 7300 feet down the runway, travelling at 40 knots. Deceleration continues until the aircraft stops after 58 seconds, 7500 feet down the runway. For this aircraft, appropriate exit locations are given in Table 2.2.

Table 2.3 illustrates the impact of varying threshold speed, airborne deceleration and runway deceleration on exit distance and time to exit. (Note that exit maneuvering time is not included in this table.) A reduction in threshold speed of 14 knots reduces exit distance by 1200 feet and exit time by 5 seconds. An increase in airborne deceleration

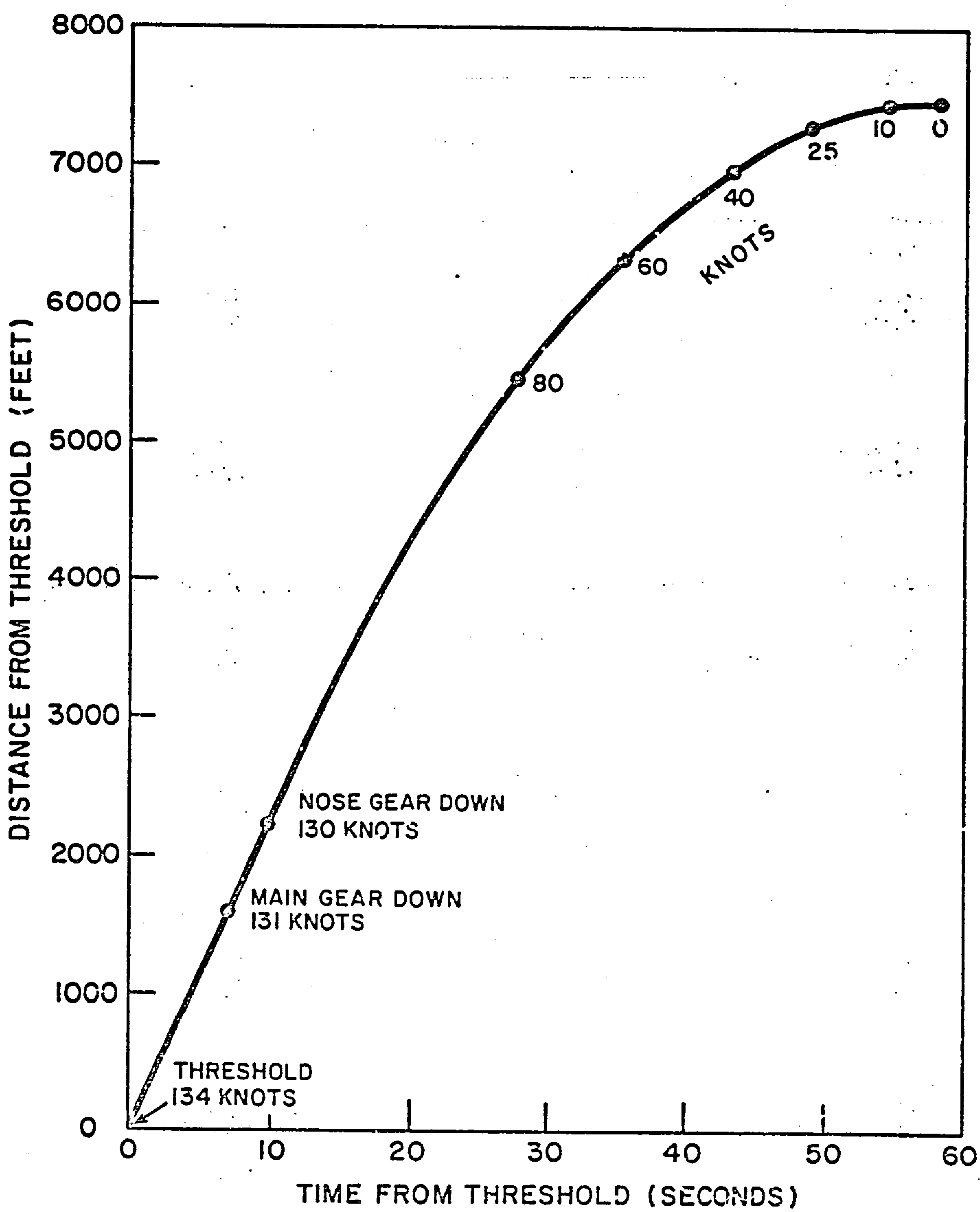


FIG. 2.4 Baseline Deceleration Profile.

Table 2.2

Influence of Exit Speed on Exit Distance and Time

Exit Speed (knots)	Exit Distance (ft)	Time to Exit* (sec)
80	5500	28
60	6300	36
40	7000	43
25	7300	49
10	7500	55

* Excludes exit maneuvering time

Table 2.3

Impact of Aircraft Speed and Deceleration on Runway Occupancy

SPEED AT THRESHOLD

Threshold Speed (knots)	Distance to Exit Speed (ft)	Time to Exit Speed (sec)
134	6300	36
120	5100	31

DECELERATION IN AIR

Airborne Deceleration (ft/sec^2)	Distance to Exit Speed (feet)	Time to Exit Speed (seconds)
0.75	6300	36
2	5700	33
4	4800	28

DECELERATION ON RUNWAY

Runway Deceleration (ft/sec^2)	Distance to Exit Speed (feet)	Time to Exit Speed (seconds)
4.5	6300	36
6	5300	29
8	4500	24

Note: Based on 60 knots exit speed

of 1.25 ft/sec2 reduces exit distance by 600 feet and exit time by 3 seconds. An increase in runway deceleration of 1.5 ft/sec2 reduces exit distance by 1000 feet and exit time by 7 seconds.

Variation of other factors can cause similar changes in exit distance in time. In practice, these values change from day to day, aircraft to aircraft, and pilot to pilot.

INTERACTION BETWEEN RUNWAY OCCUPANCY AND APPROACH PARAMETERS

Reduction in runway occupancy time will result in an increase in runway capacity only if this time is larger than the headway between aircraft using the runway. This is always true regardless of whether the runway is used for mixed operations or for landings or take-offs alone. Therefore any assessment of innovations that are introduced for the reduction of runway occupancy time has to be done with the total runway system in mind. In the final analysis, the capacity of the runway depends on the headway that can be achieved between aircraft operations. For example, in the case of landings only, the headway between aircraft crossing over the threshold will determine the capacity flow rate on the runway. If that headway is limited by the runway occupancy time of landing aircraft, then the reduction of this occupancy time will result in an increase in capacity.

Time headway between Landing Aircraft

Aircraft arriving on a common approach path have to be separated according to a set of rules. The rules generally refer to distance between aircraft and are motivated by the concern for safety from collision. Current rules stipulate that under IFR conditions the minimum separation is 3 nautical miles when neither of the aircraft in question is heavy. The prospects for reducing this separation to say 2.5 or 2 nautical miles has been the subject of considerable study and analysis. It appears that air traffic control and air navigation technology advances may make such reductions feasible. The concern with runway occupancy time is that while it does not seem to be constraining at the present time, it could become a limitation if reductions in separation become feasible from the technological and operational viewpoints.

The time headway between aircraft is related to the distance separation, or spacing between them. Assuming for the moment that all aircraft fly at the same speed, V, on the final approach to a runway, and if the spacing between aircraft is maintained at a value of D, then the time headway between aircraft (H) is given by

$$H = \frac{D}{V}$$

and consequently the flow rate on the runway reaches a maximum, or capacity, of

$$C = \frac{1}{H} = \frac{V}{D}$$

when there are aircraft waiting to land at all times. This equation indicates that while capacity is inversely proportional to the spacing maintained between aircraft, it is also directly proportional [illegible]e speed at which aircraft approach the runway. Increasing the speed will increase capacity by reducing headway even with the same spacing between aircraft.

It is interesting to note that a given time headway between aircraft can be maintained while reducing the spacing between aircraft, by reducing the speed. Thus, if it is desired to maintain time headway of 70 seconds between landing aircraft, then aircraft spaced at 3 nautical miles can fly at a speed of 154 knots; but the same headway, or time separation, can be maintained between aircraft that are 2.5 nautical miles apart flying at 129 knots. This raises the question of the extent to which safety is maintained by distance separation rather than time separation (headway) between aircraft. If headway is as effective in maintaining safety as distance separation, then it would follow that the distance separation between aircraft need not be fixed, if flying speed could be varied.

From the perspective of runway occupancy time, the distance separation between landing aircraft is of no concern; what matters is the headway. The speed at which aircraft approach a runway impacts their runway occupancy time. For example, higher approach speeds result in longer runway occupancy times. Thus, runway capacity may be increased by raising the approach speed in order to reduce the time headway between aircraft, but there is a limit to this strategy, since the increase in speed will also raise runway occupancy time to the point where it will limit the headway between aircraft, and hence the capacity. Ideally, one would wish to bring aircraft onto a runway at a speed for which the headway is exactly equal to the time required for runway occupancy that corresponds with that speed. Any higher approach speed will reduce runway capacity, while reductions in runway occupancy time below that value will not result in any increase in capacity.

Arrivals Only. To illustrate this situation, Figure 2.5 is drawn to show the relationship between approach speed and headway for a runway used only by arrival aircraft. Three curves are shown corresponding to approach spacing of 3, 2.5, and 2 nautical miles. On the same graph is shown a function referred to as RS which represents a hypothetical relation between runway occupancy time and approach speed (derived from a simulation of landing operations for which the deceleration profiles and the exit locations are held fixed). Figure 2.5 illustrates that for each approach spacing, there is only one approach speed for which the headway equals the runway occupancy time. Flying aircraft at a lower speed will create headways that are longer than the runway occupancy time and hence reduce the efficiency of the utilization of the runway; and flying aircraft at a faster speed will result in headways that are shorter than the required runway occupancy time, and hence will violate the safety procedures for runway operations.

For the RS curve used in Figure 2.5 these points of equality of headway and runway occupancy time are as shown in Table 2.4.

The gains in capacity that can be achieved from reducing aircraft spacing may not be as large as usually predicted, since reduced spacing will be consistent with lower approach speeds according to Figure 2.5 and the results shown in Table 2.4. To reduce spacing without reducing speed will result in runway occupancy time becoming a constraint and a limit to capacity.

Note that these examples are all based on average values. In real

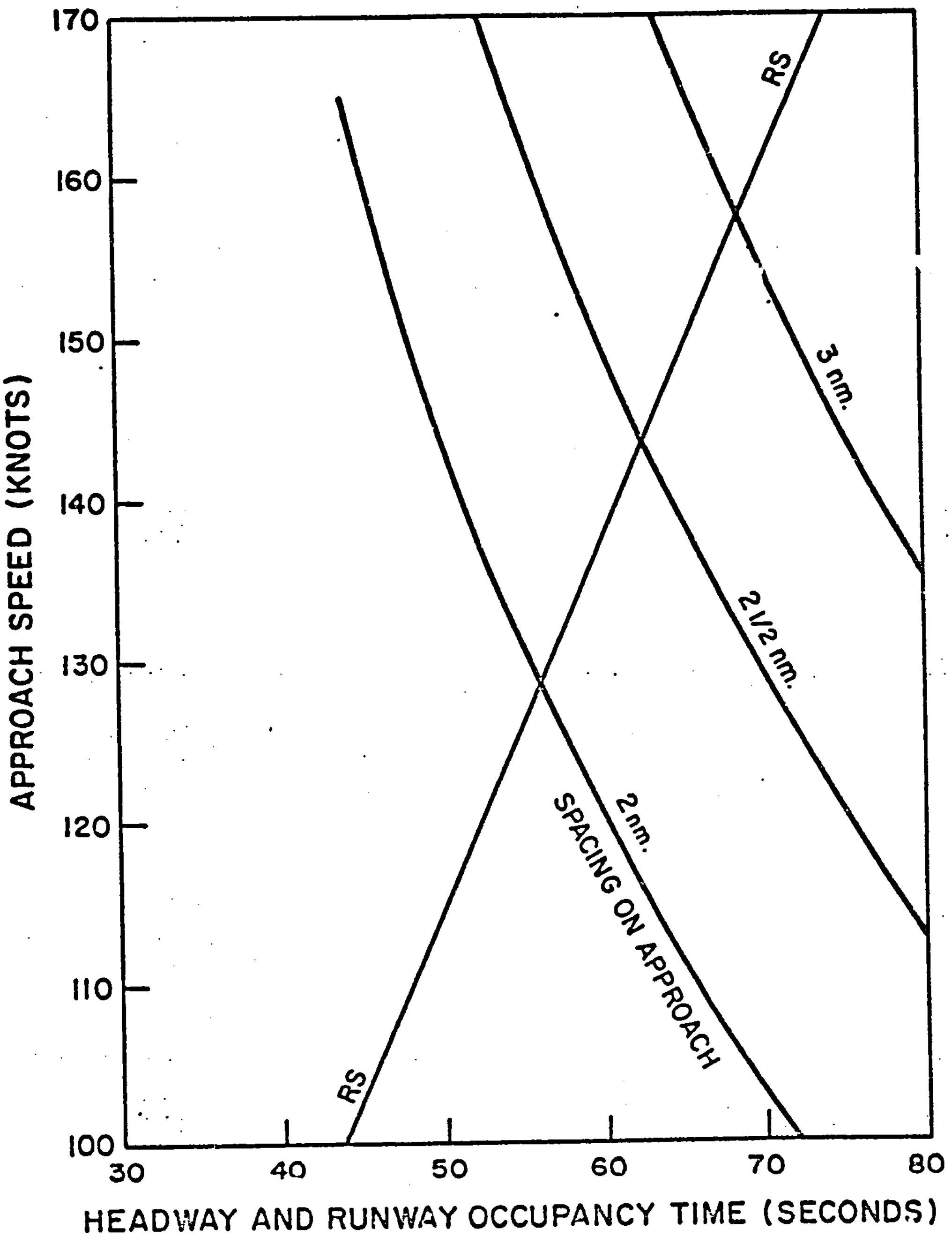


FIG. 2.5 Relationship between Approach Speed and Headway Landings Only.

Table 2.4

Runway Capacity with Varying Approach Speeds
Landings Only

Separation (nm)	Approach Speed (knots)	Runway Occupancy Time or Headway (sec)	Hourly Capacity (a/c per hour)
3	157	68.7	52
2.5	143	62.9	57
2	128	56.2	64

Table 2.5

Effect of Changing Approach Separation on Runway Capacity
Mixed Operations

Separation (nm)	Speed (knots)	Headway Between Landings (sec)	Hourly Capacity Mixed Operations (a/c per hour)
3	110	98	73
3.5	122	103	69
4	132	108	66
4.5	143	113	63
5	153	118	61

Note that these examples are all based on average values. In real life situations certain buffers may be added into the runway occupancy times and the headways in order to absorb the adverse random effects.

Figure 2.5 and the results shown in Table 2.4 also suggest that a spacing of 3 nautical miles between landing aircraft is not optimal from any point of view. The headways generated by this separation are normally too large with the speeds commonly used on final approach. They are too large in the sense that they exceed runway occupancy times. Normally one observes approach speeds in the vicinity of 120-130 knots, for which the headways with a 3 nautical mile spacing are 83-90 seconds. Runway occupancy times rarely reach these values, and the result is that the runway is not utilized efficiently. The equality of runway occupancy time and time headway occurs in this case at an approach speed of 157 knots; a speed which might be considered too high.

In cases of tailwind landing, such high ground speeds over the threshold may not be unrealistic. If the technical feasibility of high speeds over the threshold could be demonstrated, there may be a case for increasing capacity (landings only) by using the runway in the tailwind direction.

Mixed Operations.

A runway can be used either for landings, take-offs or a mixture of both. The decision usually depends on the mix of the traffic, and on the environmental conditions prevailing at the airport at the time. From the capacity point of view, it is fairly well known that it is better to alternate take-offs and landings provided there is always sufficient traffic of both types. The capacity of a runway operated with different mixes of landings and take-offs will depend on the percentage of the time operations are alternated, and the percentage of the time the runway is used for landings only and for take-offs only. Without loss of generality, we can concern ourselves here with the case of alternating landings and take-offs.

In this case, the headway between two arriving aircraft should be matched with the sum of the landing runway occupancy time of the first aircraft, and the take-off runway occupancy time of the aircraft that is interleaved between them. Assuming for the moment that the take-off runway occupancy time is fixed at 50 seconds, the graphs shown in Figure 2.5 can be extended to show the matching points of speed and headway for the mixed operations case. This can be done by shifting each of these curves to the left by an amount equal to 50 seconds (or any amount assumed for the take-off runway occupancy time). As we see in Figure 2.6, some spacings become infeasible for mixed operations as they require very low approach speeds, or very low arrival runway occupancy time. For example, the curve for 2 nautical mile spacing is no longer within the range chosen for the figure and the curve for 2.5 nautical miles is also essentially eliminated. On the other hand, one can begin to look at spacings between 3 and 5 nautical miles for mixed operations.

As with the case of landings only, the approach speed appropriate for matching headways with runway occupancy time increases as the separation between landing aircraft increases. Note that the headway between landing aircraft should equal the sum of the runway occupancy times of one landing and one take-off. With a fixed departure runway

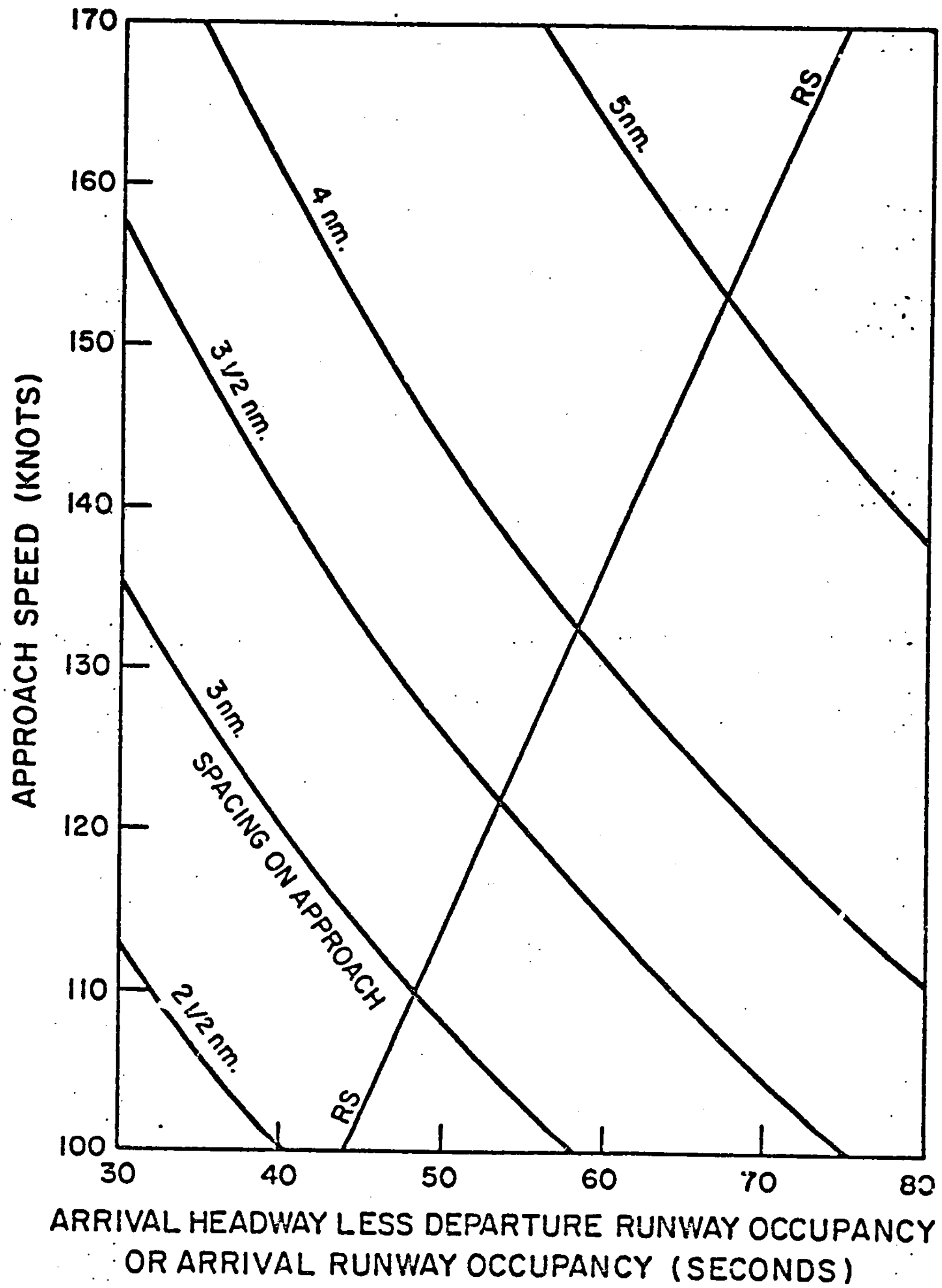


FIG. 2.6 Relati nship between Approach Speed and Headway Mixed Operations.

occupancy time (50 seconds in this example) increasing the approach speed will increase the runway occupancy time. The same trade-off occurs in this case, namely between a higher approach speed for increased capacity, and a limited approach speed for limited runway occupancy time. The capacity increase that can result from reduced spacing is not as large as one might expect. For example, even if it were technically and operationally feasible, reducing spacing by 50% from 5 nautical miles to 2.5 nautical miles does not double capacity but will only increase the capacity by 40% from 61 to 86 operations per hour. The results for different spacing are illustrated in Table 2.5.

These results are also shown together with those for landings only in Figure 2.7. Note that with the same spacing between landing aircraft, mixing operations does not yield a doubling of capacity. Optimizing the utilization of the runway by exactly matching headways and runway occupancy times, suggests a significantly higher approach speed for landings only than for mixed operations. Consequently, the capacity obtained with landings only is significantly more than half that of mixed operations. The overlap between these two cases depends on the range of possible approach speeds, and is actually quite limited. As suggested by Figure 2.7, the strategies of mixed operations and landings only overlap with the same spacing at approach speeds that are either potentially too high (for the landings only case) or potentially too low (for the mixed operations case). The extent to which one can move toward optimizing the operations of a runway, and toward reducing the effect of landing runway occupancy time, depends heavily on the range of possible approach speeds, and on the ability to vary those speeds as conditions change.

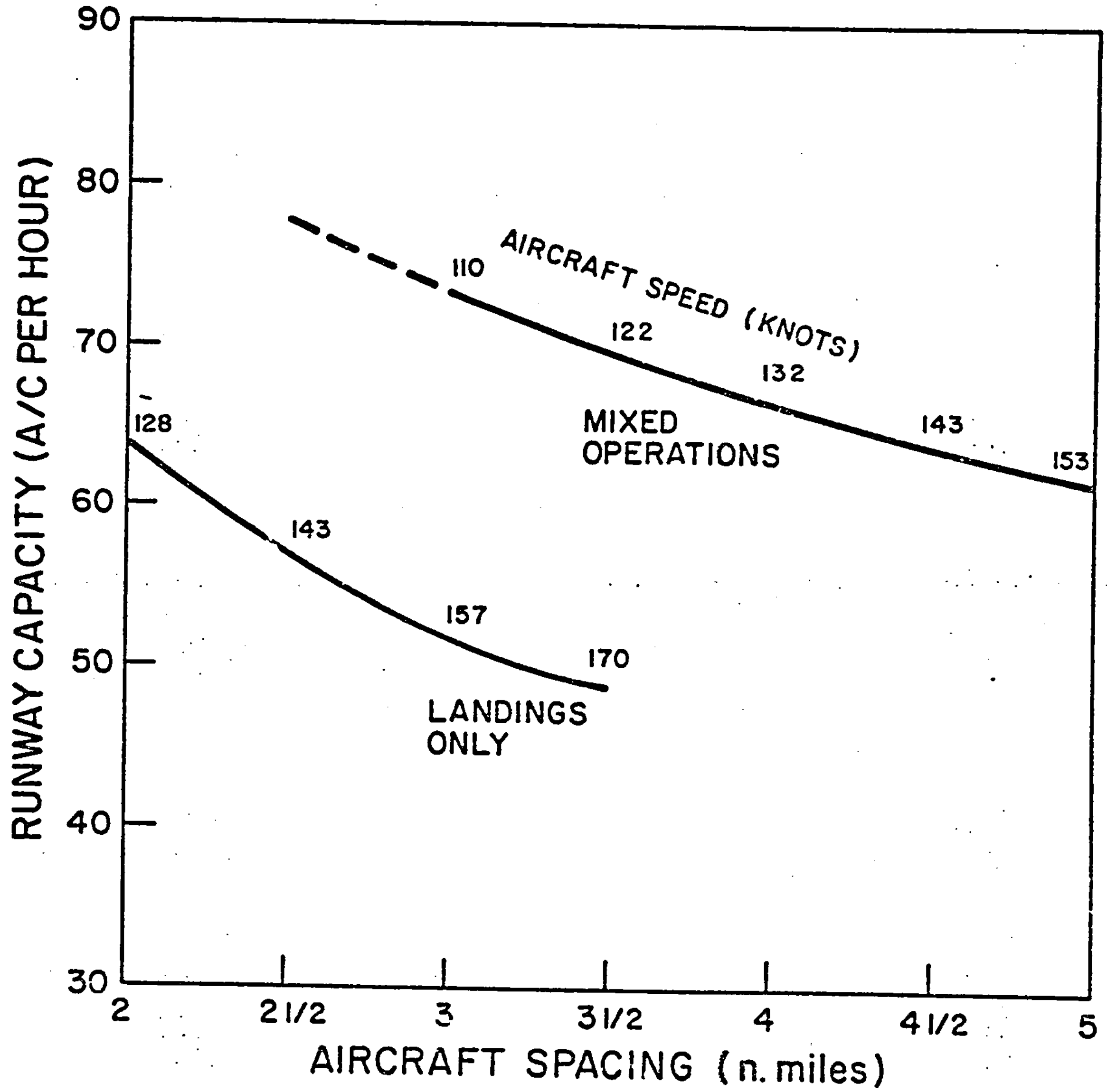


FIG. 2.7 Effect on Runway Capacity of Aircraft Spacing on Approach.

Implications and some possible innovations

The previous discussion deals with the reduction of runway occupancy times indirectly. The most important implication is that it may not be sufficient, nor useful, to look at landing runway occupancy times in isolation. The operation of a runway should be considered together with that of the final approach path, and in principle also with the operation of the taxiway system and the rest of the airfield. The discussion here is limited to the interaction between the final approach and the runway.

The potential gains from reductions in runway occupancy time will result in a gain in runway capacity provided that they are made in conjunction with corresponding adjustments to approach speed or spacing. The previous discussion suggests that there may be considerable flexibility in approach speed and spacing to achieve desired headways between aircraft. Serious consideration should be given to the concept of time separation between aircraft as a means of assuring safety.

If procedural changes are to be implemented to match headway and runway occupancy times, then a number of innovations suggest themselves. Some of those innovations are needed to implement the necessary procedural changes. Others will deal with influencing the relationship between runway occupancy time itself and approach speed. The second class of innovations is very important. because some of the potential gains from reduced spacing between aircraft may be lost because, with smaller spacing, lower speeds are necessary to match headways with runway occupancy times. If it is possible to achieve reduced runway occupancy times then it may be possible to reduce spacing without reducing speed, thereby reducing the time headway between aircraft and increasing capacity.

PREVIOUS STUDIES ON RUNWAY OCCUPANCY

The subject of runway occupancy, particularly of landing aircraft, has received considerable attention in the literature over the past twenty five years. Much of the research in runway occupancy has been directed to the related questions of runway exit design and optimal exit location.

In a series of studies in the late fifties and culminating in 1960, researchers at the Institute of Transportation and Traffic Engineering of the University of California under Robert Horonjeff evaluated high-speed exit taxiway designs and developed a mathematical model for locating runway exits.

Experiments were conducted in a joint project with the Flight Engineering Division of United Air Lines at San Francisco International Airport in which DC-6B aircraft were taxied at speed through angled exits of various configurations and the wheel tracks and speeds recorded [Horonjeff et al: 1957]. It was concluded from these tests that 30 degree angled exits were preferable to continuously curved exits, and criteria were established for the radii of the curves leading in to the exit. It was also found that a tapered exit is desirable. Such exits were found to be capable of handling aircraft at speeds up to 60 mph, if properly designed.

Later tests were conducted at McClellan Air Force Base and Wright Air Development Center for the Airways Modernization Board, using U.S.

Air Force and U.S. Navy aircraft, including jet fighters and bombers, and aircraft representative of a wide range of civil transports. The tests included runs to determine minimum permissible turning radii during runway exit, evaluation of exit taxiway configurations, methods of providing visual guidance to pilots using an exit by day and night, and aircraft stopping distance [Horonjeff _et al_: 1958]. These tests were more comprehensive than the earlier tests at San Francisco, and provided considerable information on aircraft deceleration rates and permissible radii of curvature for different aircraft types. The earlier findings on the design of high speed exits were confirmed, with a tapered entrance and 30 degree angle being preferred, although angles between 30 and 45 degrees were found to be satisfactory. Suitable configurations were developed for 60 mph exit speeds. Satisfactory daytime guidance was obtained with a 1 ft. yellow reflectorized centerline stripe. The use of centerline lights at night was found to be desirable, although no difficulties were encountered using only edge lights. A prototype centerline light fitting was developed for the tests. Based on the landing tests, exit locations were recommended for varying number of exits. Runway occupancy times for deceleration to 40 mph for the various aircraft used in the tests were found to range between 23 and 55 seconds, with about a 20% reduction in occupancy time for deceleration to 60 mph.

Based on the empirical findings of the foregoing tests, a mathematical model was developed to identify the optimum runway exit locations from the standpoint of minimizing runway occupancy, for any given number of exits and permissible exit speeds [Horonjeff _et al_: 1959]. The model was used to determine optimum exit locations for one, two and three exits with three different aircraft mixes comprised of varying proportions of large turbo-jet transports, large and medium prop-driven transports, and small general aviation aircraft, of the types used in the earlier tests. The mixes were chosen to be representative of those at different sizes of airport. It was found that the locations were very sensitive to the aircraft mix and exit speed, and ranged from just over 2,500 ft. from threshold to just under 7,000 ft. for three 60 mph exits. The study also examined briefly the concept of a higher-speed runway entrance taxiway or "turn-on", but identified a number of operational difficulties and did not pursue the idea. A later study refined the model to incorporate the effect of pilots adjusting the aircraft deceleration during roll-out to suit the actual exit location and analyzed a wider range of aircraft mixes [Horonjeff et al: 1960]. Aircraft performance data were based on a wider range of air transport aircraft, and incorporated data from observations at New York International, Washington National, and Stuttgart Airports. The optimum location for three 60 mph exits was found to lie between 2660 and 5160 ft. from the threshold. The location of each exit in the revised model was not found to be very sensitive to aircraft mix. It was concluded that aircraft types can be grouped in three classes for determining landing performance and exit location: large turbo-jet (four-engined) transports, two-engine turbo-jet and four engine propeller-driven transports, and two-engine propeller-driven transports and larger twin-engine general aviation aircraft. The exit locations were found to be virtually independent of the aircraft mix, so long as the airport was serving three classes of aircraft.

Shortly after the McClellan AFB tests, a series of observations of runway occupancy time and exit use was conducted by the U.S. Civil Aeronautics Administration (CAA) at Washington National and Indianapolis Municipal Airports [U.S. CAA: August 1958]. Runway 4-22 at Indianapolis had three curved exits with centerline radius of 955 ft. Little difference was found in the runway occupancy times of aircraft with gross landing weights over 20,000 lbs, although aircraft under 20,000 lbs gross landing weight had generally shorter occupancy times and used exits closer to the runway threshold. It was concluded that the curved exits at Indianapolis were located too far from the threshold. In all 96 landings were observed at Washington National and 224 landings at Indianapolis.

Two important reports were published in 1960, covering studies performed at Airborne Instruments Laboratory and Cornell Aeronautical Laboratory, that established the basis for the analysis of runway capacity for the next decade: "Airport Runway and Taxiway Design" [AIL: 1960] and "An Analytical Investigation of Airport Capacity" [Blumstein: 1960].

Interest in runway occupancy time in the literature appears to have waned after 1960, perhaps as a result of the reduced growth in aircraft movements and increased approach separations resulting from the introduction first of larger jet aircraft and later the new widebody equipment.

Renewed interest began developing in the mid-seventies. Joline [1974] developed a mathematical model for determining the optimum locations of runway exits, taking into account the cost of constructing the exits as well as the cost of aircraft delays. Howard, Needles, Tammen and Bergendoff performed an empirical study at a number of airports, measuring the runway performance of landing aircraft with infrared light beams, as discussed in more detail in the following section of this report. The results of this study for Runway 26L at Denver Stapleton International Airport were analyzed by Hosang [1975]. He found that essentially no aircraft used the first high-speed turnoff, partly as a result of the high landing speeds due to the elevation of the airport. Approximately one third of all landings used the second high-speed turnoff, although the figure was lower for larger aircraft and nearly 50% for smaller aircraft. Approximately 50% of all landings used the first right-angled exit after the high-speed exits. It was believed that many more aircraft could have used the second high-speed but chose the right-angled exit because of its proximity to the terminal.

During 1972 and 1973 data on airfield operations, including runway occupancy, at a number of airports were collected by Douglas Aircraft Company for the FAA. These data were subsequently analyzed by the MITRE Corporation [Koenig: 1978]. The analysis conclude that runway occupancy times are influenced by many factors including: minimum time and least number of turns to reach the gate, company procedures, incoming traffic density, flight crew performance and preference, and passenger comfort considerations. The most important factor appeared to be the proximity of the exit to the desired gate. Differences between "motivated" and "unmotivated" carriers were found to be as much as 8 seconds.

A study of the high-speed exits at Dorval and Mirabel Airports in Montreal during 1976 and 1977 [Akinyemi & Braaksma: 1979] showed that aircraft were using them at speeds 20 to 40 mph less than the design speed of 60 mph. The reasons that were identified included pilot perception of safety, incompatibility of aircraft to geometry of exit, and a different mode of aircraft roll-out than is currently assumed for design.

The Douglas Aircraft Company [Schoen et al: 1979] studied the factors affecting runway occupancy times in great detail, including touchdown dispersion, the effect of such aircraft characteristics as maneuverability and turning capability, crew functions and pilot performance, and passenger comfort. High-speed exit requirements were identified and a number of candidate exit designs developed, together with detail of a research program to enable the designs to be further pursued.

Some empirical observations of runway occupancy times were made in two studies at San Francisco International Airport [Jackson & Moy: 1979] and San Jose Municipal Airport [Morse: 1980]. An FAA study of high-speed exit taxiways [U.S. FAA: 1981] reviewed existing data on high-speed exit use, and developed design criteria and requirements for high-speed exits. Data collected in 1971 and 1972 at Malton Airport, Toronto were analyzed by Steuart and Gray [1981] to investigate the effects of weather on runway operation. They found that runway occupancy times increase in poor weather, with pilots using lower exit speeds and adjusting aircraft deceleration less to attain particular exits. The relationship between an aircraft's touchdown location and aiming point was found to be more variable in poor weather. It was also found that the true airspeed on approach tends to be lower in poor weather than in good, and that controllers attempt to adjust to poor weather conditions by increasing the margin of safety for each aircraft movement.

DATA ON AIRCRAFT PERFORMANCE ON THE RUNWAY SYSTEM

One objective of the research is the development of an improved understanding of the significant factors affecting runway occupancy. Development of this understanding depends on the availability of a data base that illustrates aircraft performance during approach, landing, and roll-out under a variety of different conditions.

The factors affecting the approach and landing process may be classified into five general categories:

1. Aircraft characteristics
2. Airport characteristics
3. Pilot technique
4. Air traffic control
5. Environmental conditions.

Within each of these categories, there are individual factors that influence the approach and landing process. For example, factors in the aircraft category include aircraft type, landing configuration, landing weight, and instrumentation.

Data requirements were defined as follows:

1. The data should include sufficient detail to allow a detailed description of the behavior of aircraft during the approach and

landing process, such as the construction of a time-space diagram for each aircraft, for example.

2. The data should include elements of the approach and landing path from outer marker to exit.

3. The data should contain or permit the derivation of the following parameters of interest:

   - Approach speed
   - Deceleration rate on approach
   - Speed over threshold
   - Height over threshold
   - Speed at touchdown
   - Distance from threshold at touchdown
   - Deceleration rate on the runway
   - Speed at exit
   - Runway occupancy time.

4. The data should contain information on the variety of factors affecting the landing process (namely, aircraft, airport, pilot, controller, and environment). Therefore the data should contain, to the extent feasible, different aircraft types, airports with different equipment and airfield layouts, pilots from different airlines, different air traffic control procedures, and various weather and visibility conditions (especially VFR and IFR).

5. The data should be readily obtainable and able to be reduced to machine-readable format with limited effort.

The various studies identified in the previous section contain various amounts of data covering the performance of aircraft on the runway and final approach. Much of the data however is very limited in scope, either in terms of what was observed or in terms of the number of observations. While helpful in obtaining a general understanding of the landing process, the limited data does not permit a detailed analysis of the influence of different factors affecting the landing process.

Three data sources were identified in the course of the study as containing rather more comprehensive data, and were examined in some detail:

- FAA airport capacity study data
- Transportation Systems Center data
- NASA head-up display simulator data.

The FAA data consists of observations at 15 airports, collected in 1972 and 1973 by a project team led by the Douglas Aircraft Company as part of an FAA airport capacity study. The Transportation Systems Center (TSC) data were collected by the TSC in late 1979 and early 1980 at five airports under a contract from the FAA. The NASA data resulted from a series of approaches and landings conducted on a Boeing 727 simulator at NASA Ames Research Center to investigate the effects of a head-up display (HUD) on pilot and aircraft performance.

In the case of the TSC data, it was necessary to perform a certain amount of data reduction, since the data were obtained in the form of films and audio tapes. The FAA data were obtained in computer-readable form, while the NASA data were provided in tabular form and transcribed to punched cards.

Federal Aviation Administration capacity study data

These data were assembled by the MITRE Corporation of McLean, Virginia from the data originally collected in a joint effort by the Douglas Aircraft Company, Peat, Marwick, Mitchell and Company (PMM), and American Airlines in 1972 and 1973 for an FAA airport capacity study. The data include information on the following:

- Aircraft velocities on final approach
- Aircraft separation
- Aircraft runway occupancy time
- Aircraft taxiing velocities
- Aircraft push-back times from gates
- Deceleration characteristics of aircraft on the runway
- Exit taxiway velocities of aircraft
- Aircraft gate utilization.

These data were initially analyzed by the firms that collected it (PMM and Douglas Aircraft Company) and were subsequently analyzed by the MITRE Corporation [Koenig: 1978]. Their main conclusions can be summarized as follows:

1. Data does not permit any categorical conclusions to be drawn but it provides some insight into the effect of aircraft type and exit location and type on runway occupancy time.

2. Runway occupancy time standard deviation for all aircraft using a runway is higher than anticipated and is higher than for those using a single exit.

3. Gate location is the most predominant motivating factor.

4. There is a potential for runway occupancy time reduction.

Different data types were collected by different groups each in a different format. For the purpose of this study, only data for the landing aircraft on approach and on the runway were analyzed. The approach data include the times when an aircraft crossed the outer marker, crossed a point 3 NM from threshold, and crossed the threshold in addition to aircraft type and flight number.

These data are contained in two data sets which were collected by two groups, one group observing the aircraft movement on approach from a radar screen and the other observing its movement on the runway from the control tower.

These two data types allow the construction of time-space diagrams for aircraft on both approach and runway. In order to construct one time-space diagram for a single aircraft that covers both approach and landing, it is necessary to find the same flight in both data sets. Of the 21 airports that were surveyed in the two phases of the capacity study, only 11 of them have both the final approach and runway data set.

Of these 11 airports, only 6 airports have matches between formats 1 and 5. In many cases only data for part of the day was found. In many of the matched observations, problems of the following kinds were encountered:

- Missing data points, to the extent that the observation is unusable.
- Discrepancy between the two data sets in aircraft type, runway number, and/or flight identification.
- Different time over threshold in the two data sets for the same flight. The difference varies from a few seconds to several minutes, and may be as much as an hour in some cases.
- Preliminary speed calculations showed that in many cases the last point recorded is unlikely to be the point at which aircraft exited, or there was a mistake in the time or the distance, since the exit speed exceeded 65 mph.
- The lists of the distances of the reference points on the runway from the threshold did not agree with the runway layout for all the reference points.

Considering the above factors, the number of usable observations was reduced to 43, as indicated on Table 2.6. A sample of the usable observations for runway 28L at San Francisco Airport were used to plot time-space diagrams, as illustrated by Figures 2.8 - 2.10.

Table 2.6

Aircraft Profile Data from FAA Airport Capacity Study

Airport	Runway	Usable Observations	Original Matches
SFO	28L	16	57
	28R	1	29
DEN	35	7	34
	26R	15	99
	8L	0	39
LGA	22	0	85
	unknown	0	5
BNA	20R	0	13
	5	1	2
	23	3	8
IAD	1R	0	21
	1L	0	4
TOTAL		43	396

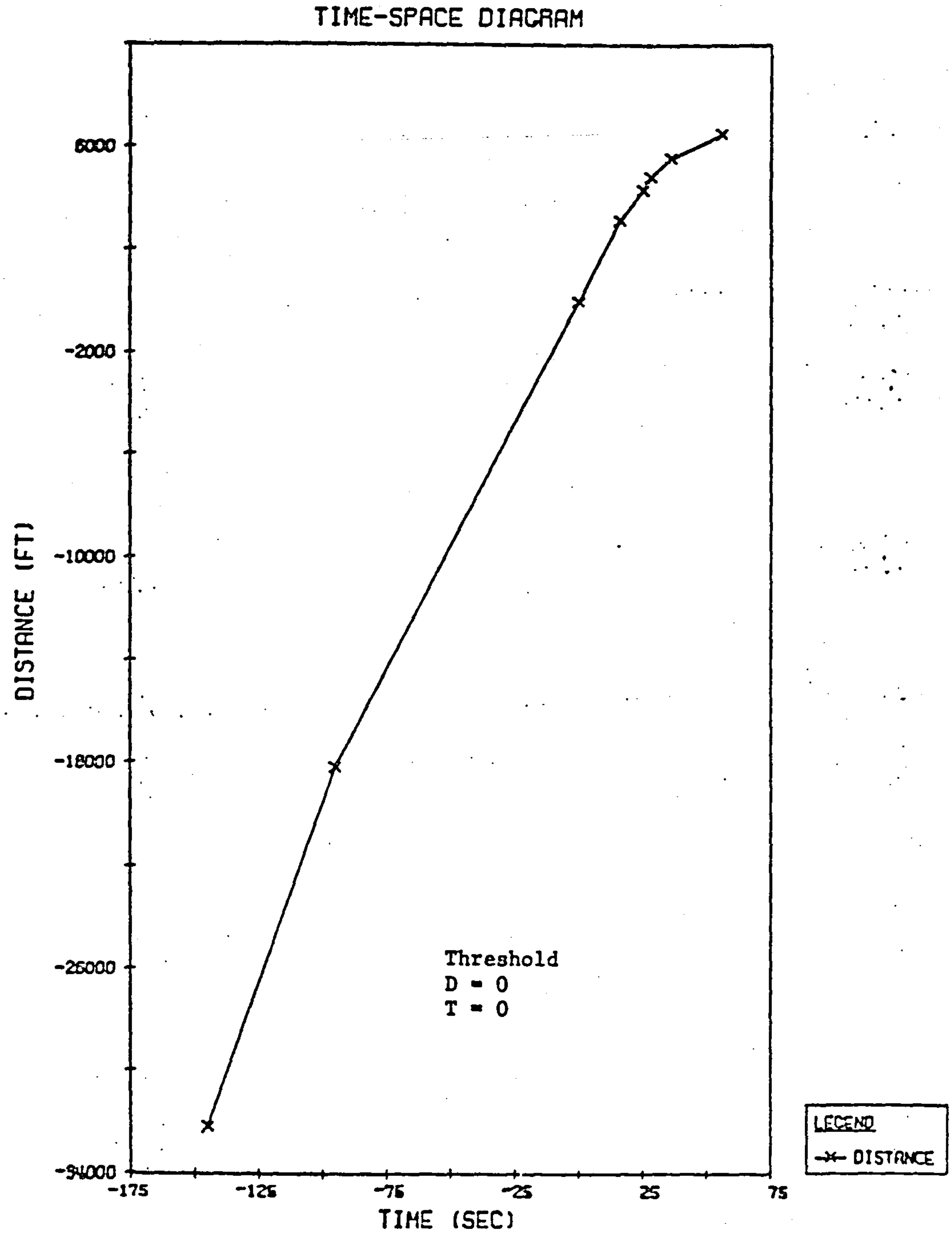


FIG. 2.8 Typical Aircraft Profile--FAA Capacity Study Data, San Francisco Runway 28L--B-747.

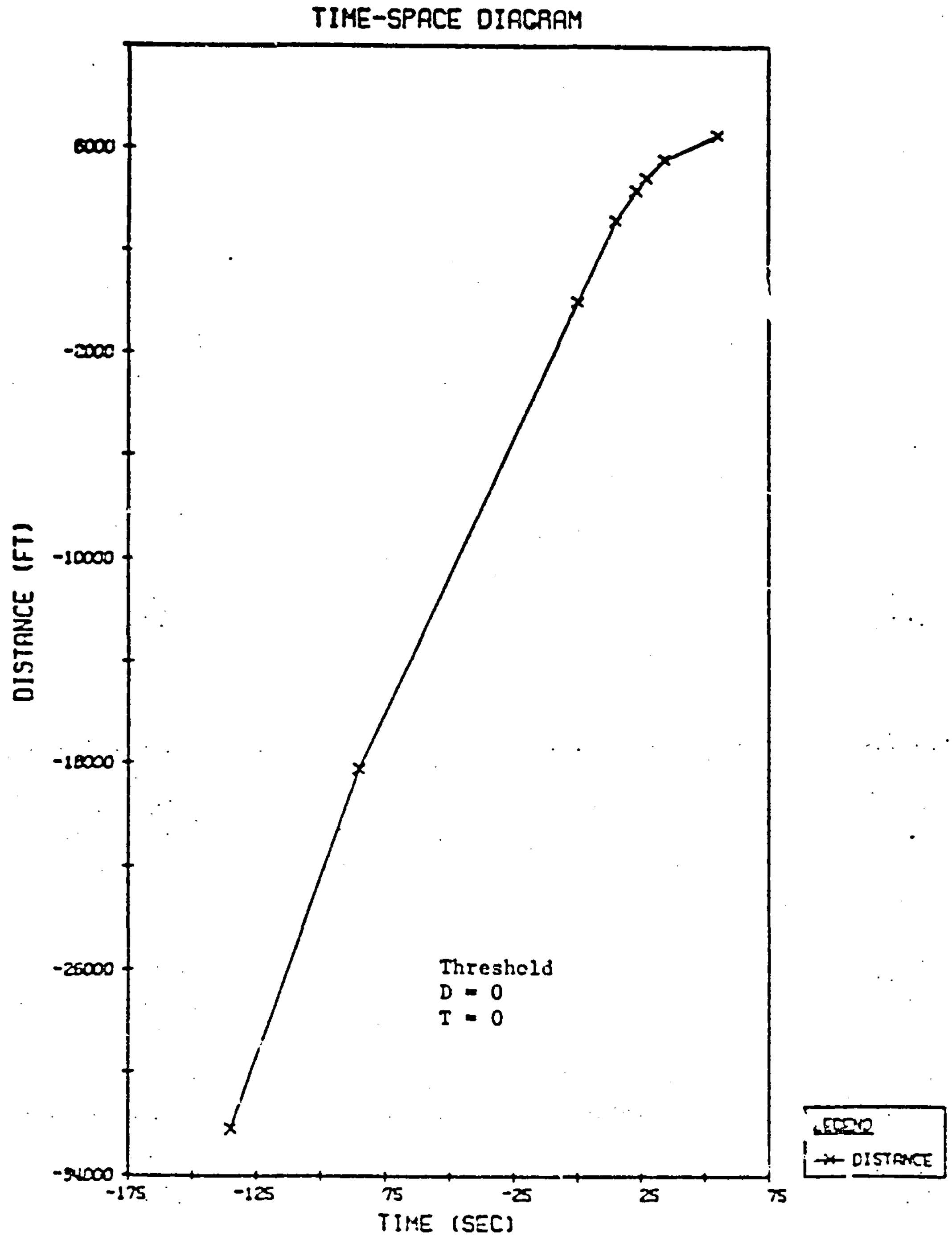


FIG. 2.9 Typical Aircraft Profile--FAA Capacity Study Data, San Francisco Runway 28L--B-707.

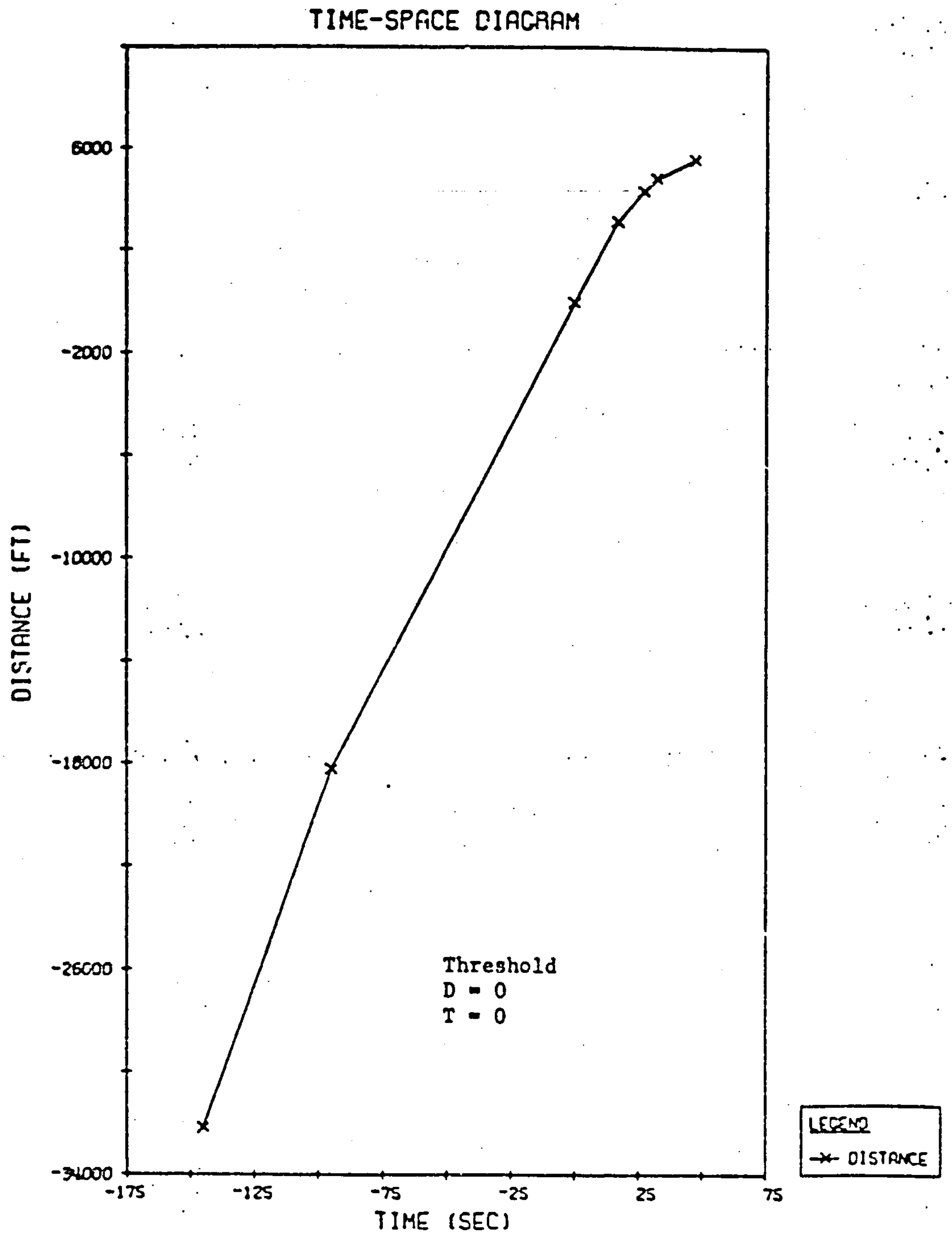


FIG. 2.10 Typical Aircraft Profile--FAA Capacity Study Data, San Francisco Runway 28L-- B-727.

These data can also be utilized in other ways than plotting the time-space diagram for the matched flights. The two data sets can be used independently to study aircraft characteristics on final approach or on the runway, such as average approach speed and average deceleration rate, for similar aircraft type, airline or runway.

Transportation Systems Center data

These data were collected in 1979 and 1980 by Input-Output Computer Services, Inc. (IOCS) of Waltham, Massachusetts for the Air/Marine Systems division of the US Department of Transportation's Transportation Systems Center, Cambridge, Massachusetts under a contract with the FAA.

The data were collected at the following five airports:

- New York John F. Kennedy International (JFK)
- San Francisco International (SFO)
- Chicago O'Hare International (ORD)
- William B. Hartsfield Atlanta International (ATL)
- Boston Logan Airport (BOS).

Three types of field data were collected at each of the five airports.

1. A movie camera was used to take 16 mm time-lapse photographs of the Airfield Surface Detection Equipment (ASDE) radar presentation as it appeared on the ASDE display unit. A digital clock (displaying hours, minutes and seconds) was included in the field of view of the time-lapse camera. The ASDE radar screen was filmed at a rate of one frame every three to four seconds. Each frame was exposed for one second, which corresponds to the time of a complete sweep by the radar.

2. Tape recordings of the local control communications were made using a voice-actuated longplay tape recorder. The tape recordings were made by connecting the tape recorder to a high quality aviation radio. A talking clock was connected to the tape recorder so that the exact time was included periodically throughout the taping of the local control communications. At the start of each data gathering effeort, the talking clock was synchronized with the digital clock used to film the ASDE display. This action facilitated the reduction of the local control tapes in conjunction with the ASDE films.

3. Tape recordings of the Automatic Terminal Information Service communications were made using an ordinary cassette tape recorder. The ATIS messages were recorded at least every hour, and if the ATIS message changed more frequently, such as during adverse weather conditions, they were recorded at each change. The information contained in the ATIS tapes has been transcribed by IOCS and the results tabulated.

In addition to the field data, an Airline Information Retrieval System (AIRS) printout was obtained for each day on which data were collected, whenever possible. AIRS printouts for several days on which data were collected were not obtained. The AIRS printouts contain a list of scheduled arrivals and departures at the surveyed airports, scheduled arrival and departure times, and aircraft types.

Data for each of the five airports were accompanied by a memorandum published by IOCS describing the contents of the data package and its quality, and the results of the local controller survey. For Boston, the report was of a broader scope and discussed the effect of different weather conditions on runway occupancy.

Each data package consisted of the following:

1. Films of the ASDE radar presentation

2. Tape recordings of the local control communications

3. Logs of the ATIS messages

4. Printouts from the Airline Information Retrieval System covering the days on which data was collected

5. A summary of an interview conducted with a person familiar with the local control position

6. A scale map of the airport facility.

In order to examine the amount and accuracy of information obtainable from these data, a small sample of data for Atlanta Airport was selected for data reduction. A sample of 20 aircraft using each of the two arrival runways in Atlanta, 26 and 27L, was reduced from the ASDE film by projecting the film on a large screen and using a specially prepared scale to measure the distance as the aircraft moves from one frame to the next. The flight numbers corresponding to the observed sample then were identified by listening to tape recordings of the local control communications. Matching the digital clock on the ASDE film and the talking clock in the recordings facilitated flight identification. The aircraft type was found either from the AIRS printouts or from the Official Airline Guide (OAG).

The runway occupancy time was calculated from the elapsed time between the moment the aircraft crossed the threshold to the time when its tail cleared the runway on exit.

During data reduction, difficulties were encountered in keeping track of the aircraft blip, in the size and shape of the blip varying, in reading the digital clock due to superposition of consecutive images, and in identifying the threshold time. The scale used allowed distance measurements to the nearest 10 feet.

The level of accuracy of the data reduction was found to be acceptable. The error in distance measurements was estimated at ± 25 feet, and the error in time measurement was estimated at ± 0.7 second.

The reduced data permitted the construction of time-space diagrams, as illustrated by Figures 2.11 - 2.13, which in turn by means of polynomial fitting allowed speed and deceleration rate estimation at various points of interest. The data also allowed other other parameters to be obtained including runway occupancy time, flight number, aircraft type, and exit used.

NASA head-up display simulator data

The NASA data were generated as part of a joint NASA/FAA project at Ames Research Center and consist of a set of 108 approach simulation runs by 9 airline pilots over 12 wind and ceiling/visibility conditions. The runs comprise a control set of conventional "head-down" approaches performed as part of a test of "head-up" cockpit displays.

All approach runs were conducted on a motion-based simulator to an 8000-foot runway with Category II lighting. Current 727-200 licensed captains from 9 different airlines were used. Each pilot conducted 12

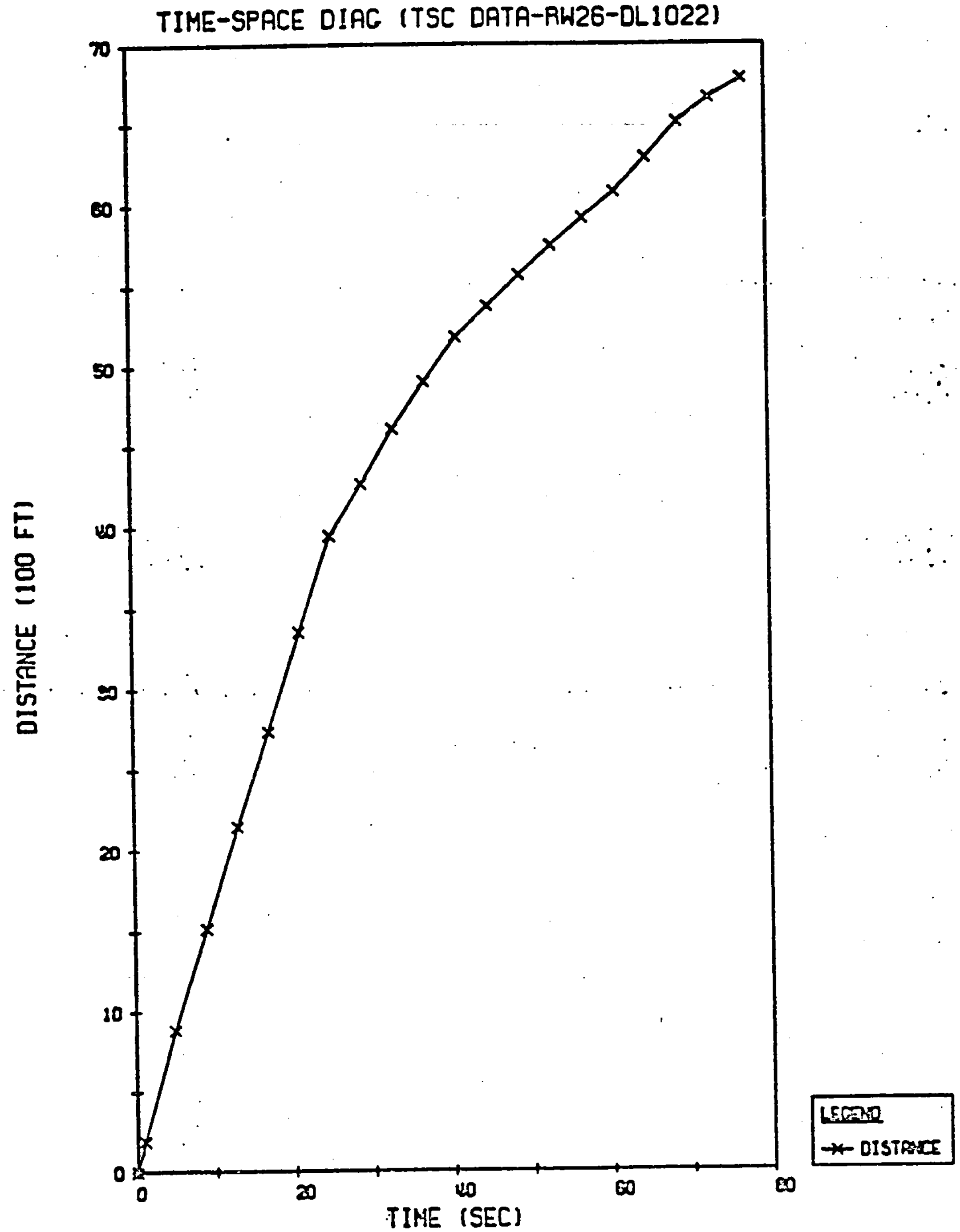


FIG. 2.11 Typical Aircraft Profile--Transportation Systems Center Data, Atlanta Runway 26--L-1011.

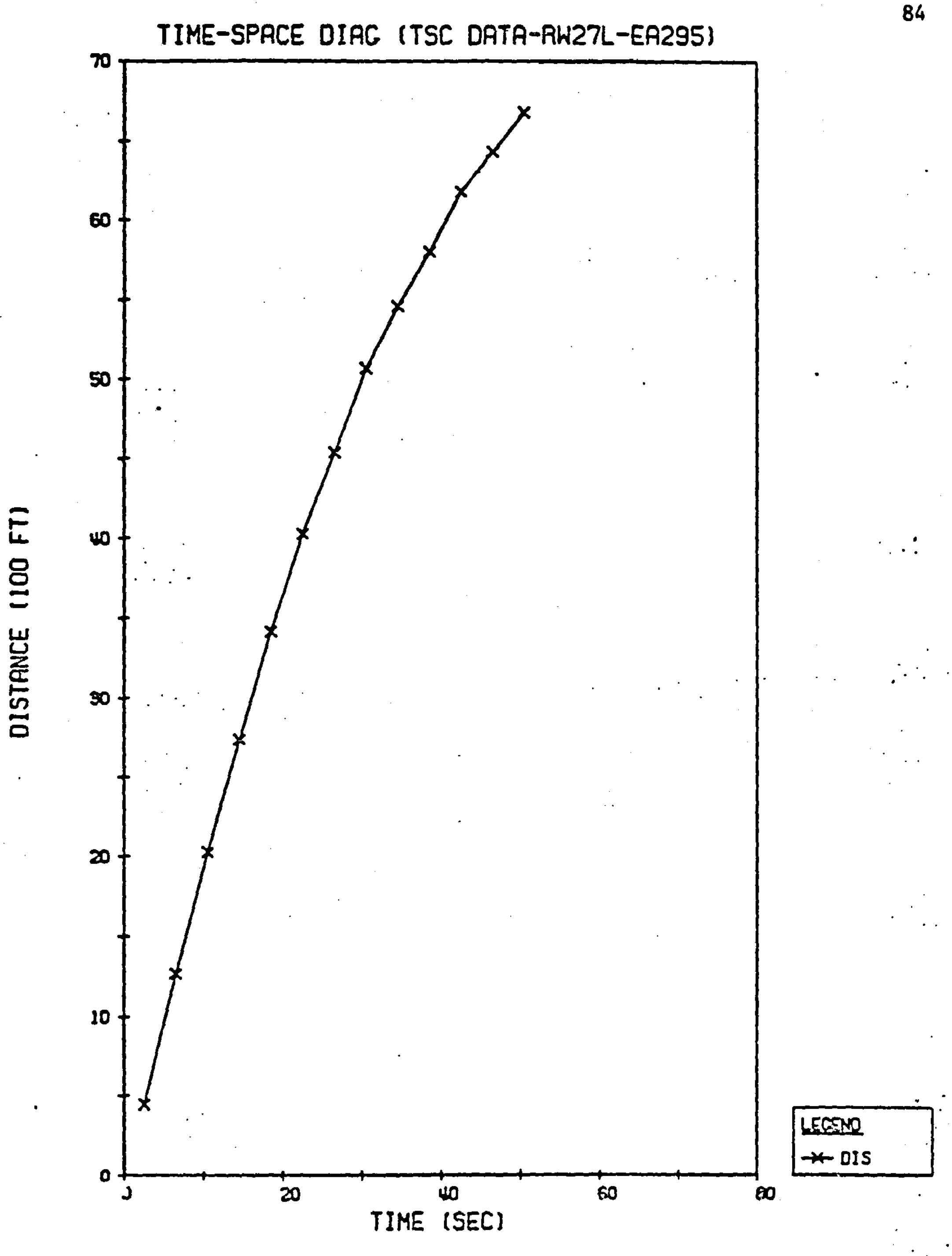


FIG. 2.12 Typical Aircraft Profile--Transportation Systems Center Data, Atlanta Runway 27L--DC-9-50.

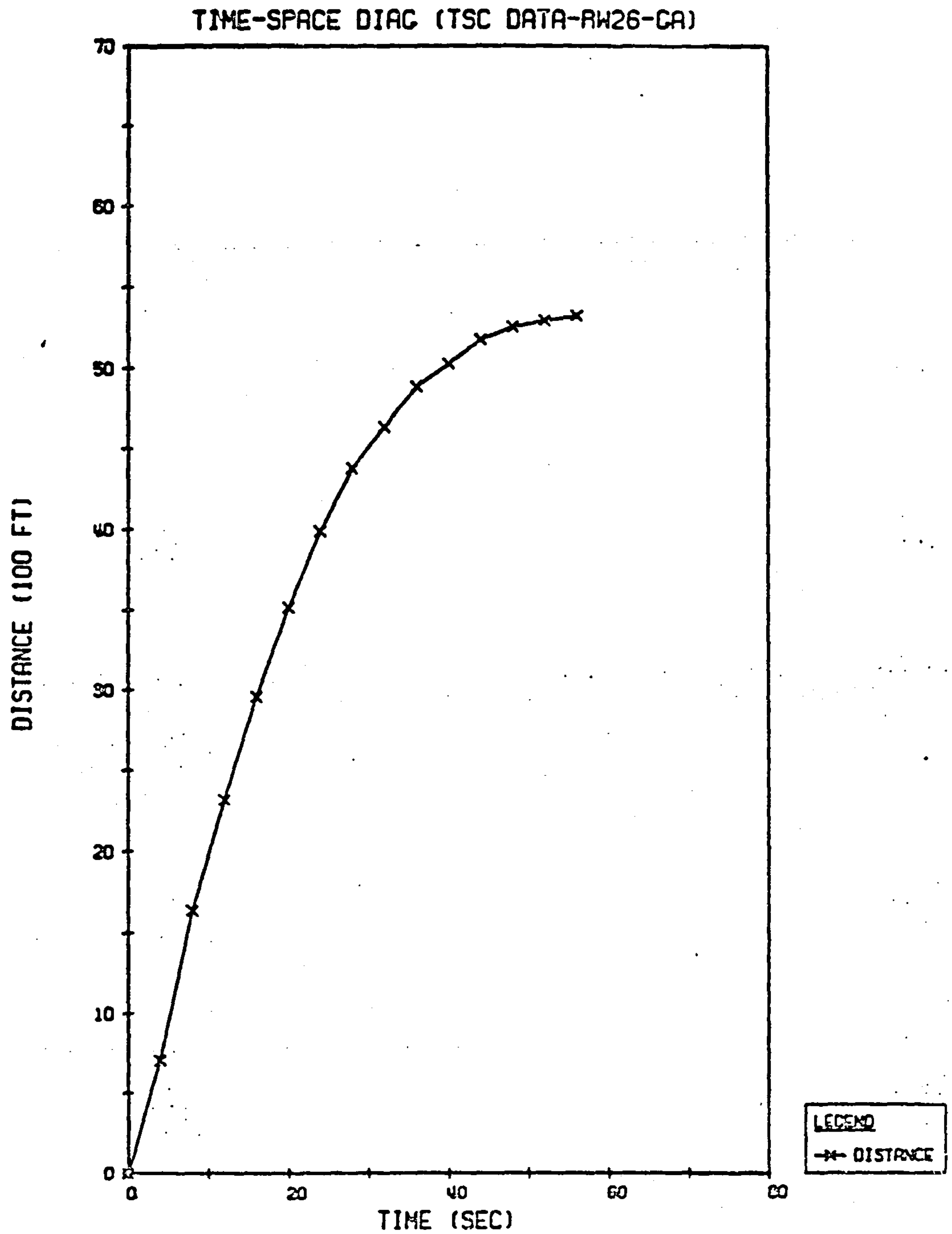


FIG. 2.13 Typical Aircraft Profile--Transportation Systems Center Data, Atlanta Runway 26--General Aviation Aircraft.

simulated approaches under various combinations of wind, ceiling and visibility conditions listed in Table 2.7. Windspeed refers to speed at threshold, with higher speeds occurring at higher altitudes; turbulence varies and includes gusts and wind shear in three directions. Precision approaches were conducted with localizer and glide slope; nonprecision approaches were conducted with localizer only. In addition, other random variations were included, such as windshear, scud (fog bank near threshold), or runway incursion. Three different "controllers" were used.

Data collected for each run included digital and analog readouts on aircraft performance, videotapes of pilot activitv, and debriefings.

Due to the large amount of data generated by the simulation runs, NASA/FAA agreed to abstract the following data from the output of the simulation runs and provide it on forms developed as part of this research project:

- NASA run number
- Condition number
- Subject number
- Air Traffic Controller (ATC) number
- Location (outer marker, middle marker, inner marker, threshold, left gear down, right gear down, nose gear down)
- Altitude (ft)
- Time (sec)

Table 2.7

Weather Conditions for Simulated Approaches in NASA Study

WIND CONDITIONS

	Type	Speed (knots)	Direction (deg)	Turbulence (RMS ft/sec)
1	Headwind	10	20	1
2	1/4 Tailwind	15	135	2
3	Crosswind	20	80	3

CEILING AND VISIBILITY CONDITIONS

	Approach	Ceiling (ft)	Visibility (mi)
1	Precision	250	0.5
2	Precision	400	1
3	Non-precision	500	1.5
4	Non-precision	800	2

CONDITION NUMBER LABELING

Ceiling/Visibility		Wind	
	Head	Tail	Cross
800 ft / 2 mi	7	8	9
500 ft / 1.5 mi	10	11	12
400 ft / 1 mi	1	2	3
250 ft / 0.5 mi	4	5	6

- Distance from threshold (ft)
- Distance from centerline (ft)
- Airspeed (knots)
- Descent rate (ft/sec)
- Thrust (% of maximum operational).

This was done for each of the 108 runs.

Upon receipt of the data, it was converted into computer-readable form. Time was converted so as to be referenced from threshold. A second set of data was created by defining nine "intervals" from the seven locations: the six intervals between the locations (outer marker to middle marker, middle marker to inner marker, etc.) plus a pre-threshold interval (outer marker-threshold), a post-threshold interval (threshold-nose gear down), and an entire run interval (outer marker-nose gear down). For each run, the longitudinal distance between points defined by the intervals, the time to traverse the interval, and the change in altitude over each interval was calculated. From these, the "interval average" groundspeed and descent rate were calculated.

The following analysis of both the "location" and "interval" data sets was performed using standard statistical analysis software:

1. Individual subject means: For each of the subjects, the mean over all conditions of each variable at each location/interval.

2. Individual condition means: For each of the conditions, the mean over all subjects of each variable for each location or interval.

3. "Grand" means: The mean over all subjects and all conditions of each variable at each location or interval.

The analysis performed in this study represents only a little of what can be done with the NASA data, and is based on each aircraft's altitude, time, position, velocity, descent rate, and thrust at seven locations. The data were used in the following way:

1. An analysis of both the interval and location data gave means and standard deviations of the variables (altitude, time, etc.) for the entire population and for sub-populations (specific conditions or subjects).

2. Using some of these results, time-space, velocity-space, and deceleration-space diagrams were drawn.

3. Tables of the variation in aircraft parameters over the 9 pilots landing under each condition and for each pilot landing under the 12 conditions were prepared. These number show the fluctuation that can occur for individual landings.

4. Histograms of the variables presented in the tables in (3) were prepared. For each variable, the runs were divided into two or more subpopulations according to a type of condition (e.g. precision vs. non-precision approaches, headwinds, tailwinds, or crosswinds).

Other data sources

Among the data collection activities performed as part of the various studies described in the previous section, one particular source of data deserves further comment, both for the quality of the data and for the technique used to collect it.

The study in question was performed by Howard, Needles, Tammen and Bergendoff (HNTB) for the US Army Engineering Waterways Experiment Station, and investigated air-carrier aircraft operations during April and May, 1974, on runways at Hartsfield Atlanta (ATL), Chicago O'Hare (ORD), and Denver Stapleton (DEN) International Airports.

The objectives of the study were to analyze the manner and extent of high-speed exit use, and to present in tabular and graphical form information describing:

1. Aircraft touchdown locations and exit utilization.
2. Aircraft speeds at various points along the runway and at the point of runway turnoff.
3. Runway occupancy time for aircraft using each exit.

The information is presented by aircraft type and model for the operational conditions encountered and, to the extent that the data were sufficient to make segregation meaningful, according to whether day or night, pavement condition (wet or dry), and relative magnitudes of headwinds.

Data were obtained from measurements using arrays of infrared light beams placed at particular locations along each runway. The arrays consisted of one or three light beams, referred to as "I" and "N"-type arrays, respectively, from the geometric layout of the beams in each array type. The light transmitter and receiver units were oriented so that the light beams were projected across the runways at approximately aircraft wheel-level height and, except for the diagonal beam in "N"-

type arrays, at 90 degrees to the runway centerline. Passage of an aircraft through an array caused interruptions of the beams.

The "N"-type arrays determined aircraft lateral position and speed at the array locations along the runways. The "I"-type arrays, in conjunction with the parallel legs of "N"-type arrays, determined the intervals along the runway within which aircraft touchdowns and turnoffs occurred, from the first and last beams interrupted.

For each recorded landing, the aircraft speed at each "N"-type array crossed, the aircraft identity, and the identity of the first and last interrupted beams were stored in the data base. Also stored for each recorded landing was information describing the weather and runway conditions, including ceiling height, visibility, precipitation type (if any), barometric pressure, temperature, wind speed and direction, pavement condition (wet or dry), and runway lighting (day or night, runway lights on or off).

Aircraft speeds were accurate to within one foot per second, or better. The points of touchdown were deemed to be at the midpoints of the runway intervals (defined by the transverse light beams) in which the touchdowns occurred, and were therefore accurate to within one-half the length of the runway intervals.

A detailed description of the data-collection system and its operation is provided in FAA Report No. RD-74-36, "Field Survey and Analysis of Aircraft Distribution on Airport Pavements" [HNTB: 1975].

FACTORS INFLUENCING RUNWAY OCCUPANCY TIMES

There are a large number of factors that influence the runway occupancy time of a landing aircraft. One can identify these factors from a consideration of the landing process of a particular aircraft on a given runway. The time required for an aircraft to reach an exit at a speed appropriate for that exit (for the prevailing environmental conditions) depends on the location and design of the exit the approach speed of the aircraft, and the deceleration rate applied by the pilot upon landing. These factors depend in turn on the type and configuration of the aircraft, on the prevailing environmental conditions (visibility, wind and runway surface condition), and on the combination of reverse thrust and braking which a particular pilot applies the deceleration necessary to reach exit speed. The relation between aircraft performance and the prevailing environmental conditions also depends on the nature of the navigation and landing aids available at the airport in question, and is likely to vary depending on pilot behavior, and familiarity with the airport. The occupancy time of the landing aircraft will of course depend on the choice of exit. From the exits that are feasible for a given operation, a pilot is likely to select the one that puts the aircraft on a taxiway closest to the terminal where the aircraft is destined. This can affect runway occupancy significantly.

In order to organize the process of identifying which of these factors will have the predominant effect on runway occupancy time, they are grouped into five categories related to the following:

1. Airport design and equipment characteristics

2. Performance characteristics of the aircraft

3. Airline procedures and pilot behavior

4. Prevailing ambient weather and visibility conditions

5. Navigation and landing aids and procedures.

The data available were reviewed in an attempt to single out the most significant factors in each of these categories.

It is not possible to identify a single most significant factor of all those influencing runway occupancy time, nor is it necessary to do so. The many factors at play interact in a rather complex way, and it is partly due to this interaction that statistically significant inferences regarding the quantifiable effects on runway occupancy time cannot easily be obtained.

Airport Design and Equipment Characteristics. With respect to the first category of factors, it is clear that the location of exits has a significant impact on runway occupancy time. This impact is more significant than the specific design characteristics of each exit in influencing which exit is used.

Some of the data analyzed illustrate this effect rather clearly. Of a sample of landings on Runway 27L at Atlanta International Airport, the aircraft using the first exit showed a mean runway occupancy time of 44 seconds with a standard deviation of 4 seconds; those using the second exit had corresponding values of 56 seconds and 5 seconds respectively.

The design of an exit also affects runway occupancy time by influencing the time for the exit maneuver. In turning onto an exit, an aircraft has to undertake a maneuver that takes anywhere between 5 to 25 seconds. It has been observed, and was noted in the data analyzed, that heavy widebody aircraft will take the longest times for this maneuver, particularly when turning onto right- angled exits. Some airlines have policies that require pilots to slow down to low speeds (e.g. 10 knots) before executing such turns. The combination of exit location and design can therefore be a significant determinant of runway occupancy time.

Performance Characteristics of the Aircraft. From the second category of factors, the size of the aircraft is perhaps the most significant. Smaller aircraft have typically shorter occupancy times. They appear to land closer to the threshold, and to decelerate faster to exit speeds. Other than the distinction between widebody and narrow body aircraft, the data examined do not show any further differences between specific aircraft types. In-depth analysis of these and other data might disclose further differences.

Airline and Pilot Behavior and Practices. The third category of factors has influences that can only be inferred indirectly from the data. Similar aircraft from different airlines have been observed to select different exits presumably due to the proximity of the taxiways to their respective terminals and this has affected occupancy times. Furthermore, variations in the landing performance of different pilots suggest that the many parameters of the landing process that are at the discretion of the pilot result in different occupancy times under similar conditions. Airline and pilot motivation are therefore seen as important factors.

Prevailing Ambient Weather and Visibility Conditions. Weather conditions are important factors influencing occupancy time. The conditions of the runway surface (e.g. dry, wet) influence the amount of deceleration that aircraft are capable of achieving or the pilots are willing to apply. Furthermore, in wet runway conditions, exit speeds are lowered and exit maneuvers take a longer time. Other parameters of the landing process, such as height over the threshold and the location of touchdown point do vary with weather conditions, but the amount is not easily discernible from the available data.

Navigation and Landing Aids and Procedures. The presence of landing and navigation aids appears to influence occupancy time indirectly. Precision approaches appear to result in smaller variations in some parameters of the landing process such as height over the threshold and touchdown point. They also appear to result in lower mean occupancy times as a consequence of the lower heights and earlier touchdown points. Good lighting and marking are bound to have an effect on the landing process although such effect could not be quantified from the available data.

3. POTENTIAL INNOVATIONS TO REDUCE RUNWAY OCCUPANCY

As the interaction of the various factors influencing runway occupancy time has become better understood, strategies for reducing runway occupancy times have been developed. These strategies utilize one or more specific measures or innovations (the term innovation includes both measures not previously considered as well as significant improvements or changes to existing technology or procedures). The approach adopted in this study has been to identify as wide a range of potential innovations as possible, then to subject these innovations to an evaluation process that leads to the selection of a relatively small number of promising measures for more detailed analysis. This chapter describes the identification process and the range of potential innovations identified, the development of the evaluation criteria, and the results of a preliminary evaluation of the innovations to identify those deserving closer examination. This approach considers the use of the runway from the perspective of a single innovation in each case. However in any complex system, one particular change is likely to affect the consequences of any other. Thus it is necessary to recognize that many of the individual innovations identified will interact with other innovations.

IDENTIFICATION OF POTENTIAL INNOVATIONS

By its very nature, the process of developing a list of innovative measures to influence runway occupancy time cannot be reduced to a simple set of rules. Some ideas have already appeared in the literature in one form or another. Others follow from a consideration of the factors involved.

The arrival and departure processes involve a number of different components, from the aircraft itself and its interaction with the airport facilities, to the actions of the pilot and the air traffic control system rules and procedures. These components provide a structure for considering individual innovations, which generally fall into one of the four categories:

- Aircraft
- Airport
- Pilot
- Air traffic control/Federal aviation regulations (ATC/FAR).

As with any classification system, not all topics fit neatly into one of the above categories and some innovations may appear to fit more than one. The actual classification is therefore somewhat arbitrary. In addition, certain innovations presume the existence of other measures or suggest other complementary innovations.

In all, fifty eight individual innovations were identified. These are listed on Tables 3.1 - 3.3.

Aircraft innovations

Potential innovations in aircraft technology consist of measures to improve the aircraft performance on the runway, or improvements in landing aids and instrumentation in order to improve the pilot's control over the aircraft path and reduce variation in performance.

Measures to increase the deceleration capability on the runway

Table 3.1

Aircraft Innovations

1.	Increase deceleration capability
	a. reverse thrust
	b. improved braking
	c. increased drag
	d. arresting devices
2.	Increase exit turn capability
	a. improved steering and gear
	b. improved tires
3.	Decrease threshold speed
	a. increased lift coefficient
	b. lower stall speed margin
	c. powered lift
	d. variable geometry
4.	Improve landing aids
	a. head-up display
	b. autoland
	c. NAVSTAR/INS
	d. improved pilot view
	e. runway guidance
5.	Improve instrumentation
	a. ground speed
	b. CDTI
	c. ambient condition display
6.	Improve go-around performance
7.	Reduce aircraft weight

Table 3.2

Airport Innovations

1. Locate exits to minimize occupancy
2. Location of runways, taxiways and terminals
3. Location of circulation taxiways
4. Optimize width of airfield elements
    a. runways
    b. exits and fillets
    c. taxiway turns
5. Match exit radii to aircraft performance
6. Improve exit marking and lighting
7. Improve landing aids
    a. VASI/approach lights
    b. ILS/MLS
    c. pavement marking
8. Improve runway surface friction
9. Improve runway entrance location and design
10. Additional runways
    a. close parallel/short parallel
    b. V-runways
    c. variable width/double width
11. Install arrester devices
12. Aircraft guidance wire in pavement
13. Improve runway safety areas
14. Deceleration gradients
    a. runways
    b. exits

Table 3.3

Pilot and ATC/FAR Innovations

PILOT INNOVATIONS

1. Standardize landing and roll-out procedures
2. Pilot motivation
3. Remove airline restrictions
4. Improve pilot information
   a. exit location
   b. environmental conditions

ATC/FAR INNOVATIONS

1. Permit multiple occupancy
   a. left-right/short-long
   b. arrivals-departures
2. Enforce exit selection
3. Lower threshold height
4. Designate taxiway to local control
5. Sequence aircraft by occupancy characteristics
6. Improve controller information
   a. aircraft speed and acceleration
   b. aircraft characteristics
   c. pilot intentions
7. Automate departure and go-around decisions
8. Establish approach tolerance limits
9. Modify final approach path

include increasing the reverse thrust available, improving the braking capability, increasing the aerodynamic drag after touchdown, and the use of mechanical arresting devices. While increasing the deceleration on the runway will clearly reduce the time needed to reach exit speed, a further reduction can be achieved by using reverse thrust or aerodynamic drag to increase the deceleration while airborne between the threshold and touchdown, leading to an earlier touchdown at a lower speed. Increasing the power available for reverse thrust could also lead to reduced departure runway occupancy if this increased thrust is also available for acceleration.

Runway occupancy can also be reduced if aircraft can exit at a higher speed. Improvements in steering, landing gear and tires would enable pilots to exit at a higher speed or to take sharper radius curves.

A decrease in threshold speed will generally result in reduced runway occupancy due to the lower amount of deceleration required. This can be achieved by increasing the lift coefficient in approach configuration, reducing the margin between stall speed and approach speed, or utilizing such measures as powered lift or variable geometry.

Improvements in landing aids that would help maintain the precision of the approach and provide additional guidance to that currently available include cockpit head-up display, automated landings, new navigational equipment based on satellite navigation or inertial navigation systems (INS), improvement of pilot view from the cockpit, and aircraft guidance on the runway.

Additional instrumentation includes a ground speed indicator, cockpit display of traffic, and an ambient condition display. These instruments would assist pilots in selecting the most efficient approach speed and permit closer airborne spacing.

Improved go-around performance would effectively reduce runway occupancy by permitting a trailing aircraft to continue its approach longer when the lead aircraft is slow to clear the runway. A reduction in aircraft weight would improve acceleration and deceleration and reduce touchdown speeds.

Airport innovations

Airport innovations consist of measures to improve the design of airfield elements, changes in airfield configuration, measures to provide pilots with improved visual reference and aircraft guidance, and measures to enhance aircraft deceleration.

Design changes for airfield elements include the location of exit taxiways to minimize runway occupancy in the light of the expected fleet mix and performance characteristics; changing the width of runways, exits, fillets and taxiway turns to encourage higher speeds and earlier exits; matching exit radius to expected aircraft performance; improving runway entrance location and design to permit more rapid initial acceleration on takeoff; improving the design of runway safety areas to encourage pilots to make more use of potential aircraft performance on the runway; and the use of deceleration gradients on runways and exit taxiways.

Changes in airfield configuration that would tend to reduce runway occupancy include the location of runways, taxiways and terminals so that the optimum exits from the standpoint of runway occupancy give the shortest taxi time to the gates. Circulation taxiways should be located so that they do not infringe on exit runout distances. At some airports it may prove possible to provide additional runways within the available site constraints by using closely spaced or short, special-purpose parallel runways, or V-configuration runways with single or dual approach streams. More innovative approaches include variable width runways to permit aircraft to pass on the runway if necessary or very wide runways permitting alternating left-side, right-side operations.

Improved landing aids such as Visual Approach Slope Indicators (VASI), approach lighting, instrument and microwave landing systems (ILS/MLS), and pavement markings can provide improved pilot guidance in order to reduce variation in aircraft performance and ensure more consistent use of exits. Electronic guidance on the runway during poor visibility, or to identify exits, can be provided by means of a guidance wire system in the pavement.

Deceleration performance can be enhanced by improvements in runway surface friction or the installation of mechanical arresting devices. While the latter may not be feasible for routine operations, they may present a viable safety measure to permit tighter operating tolerances or other innovations.

Pilot innovations

Pilot innovations consist of measures to reduce variation in pilot technique and increase incentives for pilots to achieve lower runway occupancies.

Standardization of landing and roll-out procedures will reduce variation between different airline practices and individual pilot technique. Where individual airline operating restrictions limit pilots' utilization of all available exits, these should be examined for consistency with other carriers and their removal or modification proposed where possible.

Airlines can be encouraged to motivate their pilots to exit as quickly as possible by stressing the economic consequences of the trade-off between capacity induced delay and factors such as passenger comfort and tire wear. Pilot motivation will also be enhanced by dissemination of information on the safety and cost implications of particular practices.

Pilot technique may also be improved through the provision of improved information on runway exit location and prevailing environmental conditions.

ATC/FAR innovations

Changes to existing air traffic control procedures and regulations can improve runway occupancy by eliminating restrictions that result in periods when the runway is not being used, or by modifying the aircraft's approach path and exit use.

The existing restriction on multiple occupancy of a runway could be relaxed by restricting dual occupancy to alternate sides where sufficient clearance exists to permit aircraft to pass, or by longitudinal separation with sufficient distance on the runway that the trail aircraft can come to a full stop or exit before reaching the lead aircraft. Arrivals and departures may also be able to safely use a runway simultaneously under certain circumstances.

More efficient use of the runway may be achieved by designating the exit to be used, sequencing aircraft by their occupancy characteristics, and improving the information available to the controller on aircraft speed and acceleration, aircraft characteristics such as weight, and pilot intentions. Full use could be made of potential slots for departures, and unnecessary wave-offs could be eliminated, by automating departure and go-around decisions with a system that combines speed and spacing monitoring with a conflict prediction capability.

By including parts of the taxiway system under local (tower) control, aircraft would no longer have to be able to stop or change frequencies before entering the taxiway system, permitting higher exit speeds and reducing pilot workload.

Reduction of glide path height over threshold and changes in the slope of the final approach path will reduce time from threshold to touchdown, while reducing the length of the final approach path will reduce the headway between aircraft of dissimilar speeds. Establishing approach tolerance limits could help reduce long runway occupancy times by improving approach precision and by early identification of the development of an extreme occupancy time.

DEVELOPMENT OF EVALUATION CRITERIA

Each of the potential innovations under consideration generates some benefit in terms of reduced runway occupancy or reduced threshold headway. However this benefit is not a fixed quantity, but depends on the extent of implementation of the innovation. One cannot therefore simply compare the benefits to be obtained from each innovation. Some account must also be taken of the costs and other consequences of any particular level of implementation. While this suggests a classical cost-benefit analysis, this was not considered an appropriate approach for this study for two reasons. Firstly it was recognized that each innovation involved many different costs and other impacts, and it was not felt to be feasible within the resources of the project to attempt to assess these to the level required to determine dollar values. Secondly the nature of many of the impacts is such that there was considerable doubt that dollar values could be determined that would receive general acceptance.

The alternative approach that was adopted was to identify three types of evaluation criteria:

- Benefits
- Required changes in the system
- Side effects.

Nineteen individual criteria were initially identified within these three classes as indicated on Table 3.4.

Table 3.4

Initial Evaluation Criteria

1.	Reduction in mean and variance
2.	Predictability of ROT
3.	Capital cost
4.	Need for new technology
5.	Need for new facilities and equipment
6.	Need for new procedures
7.	Implementation time frame
8.	Institutional acceptability
9.	Suitability for retrofit
10.	Safety impact
11.	Noise impact
12.	Pilot workload
13.	Controller workload
14.	Go-around probability
15.	Aircraft separation
16.	Aircraft fleet mix compatibility
17.	Land requirements
18.	Passenger comfort
19.	Airport impacts

Benefits

Benefits consist of both an actual reduction in the mean runway occupancy time or the variation in runway occupancy, or an increase in the predictability of the runway occupancy. Reducing the occurrence of long runway occupancy times will decrease the size of the buffer needed between successive aircraft. Reducing average runway occupancy times will permit closer spacing between landing aircraft or more departures during mixed operations. Even with widely varying runway occupancies of successive aircraft, capacity gains can be achieved if these can be anticipated in advance and the spacing of successive aircraft on the approach adjusted to utilize the runway availability created by the shorter occupancies.

Requirements

Requirements for implementing a particular innovation were considered to include both the capital costs involved in obtaining or modifying the necessary facilities or equipment, and the costs associated with the need to develop a new technology or utilize existing technology to develop new facilities and equipment, and to establish new procedures. In addition it was recognized that different innovations required different time frames for implementation and would present different degrees of difficulty in achieving institutional acceptability. It is also desirable that aircraft innovations are suitable for retrofitting to the existing aircraft fleet.

Side effects

Potential side effects that were identified as resulting from an innovation include safety and noise impacts and changes in pilot and controller workload or passenger comfort. Increases in go-around probability reduce capacity and impose additional aircraft operating costs. Changes in aircraft separation on approach, leading to a reduction in airspace capacity, could negate any gains in reducing runway occupancy. Some innovations would affect compatibility between different types of aircraft in the fleet mix. Innovations requiring additional land were seen as creating difficulties at many airports beyond the question of the acquisition cost. There are also particular impacts that might be created by some innovations at particular airports, due to the airport configuration or other factors.

Structure of the evaluation

The foregoing categories provided the initial framework for evaluating the individual innovations. However the requirements as identified omit explicit reference to operating costs while the costs involved in developing new facilities and equipment can be accounted for in the other costs. Implementation requirements can be translated into the costs associated with development and approval of new procedures, and the cost of training and familiarization programs.

The benefits in terms of runway occupancy parameters can be used to infer the consequences for changes in capacity under given airport and fleet mix conditions. The effects of changes in go-around probability and aircraft separation can be allowed for in the effect on capacity and operating cost.

Thus a modified evaluation strategy was developed for more detailed consideration of specific innovations. This strategy addresses:

- Benefits
- Costs
- Impacts
- Other considerations.

The benefits are assessed in terms of an arbitrary baseline situation consisting of an airport with a single runway with 30° angled exits at 5000 feet and 7000 feet from the threshold and an aircraft mix consisting of equal numbers of arrivals and departures with 10% heavy and 10% small aircraft. From estimated changes in the runway occupancy characteristics, the changes in runway capacity are projected using the FAA runway capacity model (FAA:1974). Estimates of other quantifiable benefits, such as reduced operating costs, are also made.

Costs are assessed in terms of order of magnitude for both capital costs and operating costs of the aircraft, the airport and the ATC system. New technology requirements are expressed in terms of the scale of funding likely to be required to develop the technology. In addition, implementation costs are also considered.

Special account is made of safety and noise impacts, likely changes in pilot and controller workload, and passenger comfort.

A number of issues do not easily lend themselves to quantitative analysis and are generally given a more qualitative treatment. These include:

- Likely lead time for implementation
- Ease of application to existing aircraft fleet and airports
- Compatibility with non-improved aircraft or airports
- The relative pace of development of benefits with incremental implementation
- Incidence of benefits and costs across aircraft fleet and airports
- Timing of pay-off and relative magnitude of research and development for new technology
- Availability of existing funding procedures
- Consequences of equipment failure and system degradation along a safe path.

Only those issues that are believed relevant to a particular innovation are given consideration in that evaluation.

PRELIMINARY EVALUATION

The fifty eight individual innovations described in Chapter 3 above and listed on Tables 3.1 - 3.3 were subject to a preliminary evaluation according to the nineteen criteria given on Table 3.4. For each one of the criteria, each innovation was assessed as having a favorable, neutral, or unfavorable impact in terms of that criterion. For those innovations for which it was felt the criteria had no meaning, such as the suitability for retrofit of innovations other than aircraft innovations, no assessment was made.

In the case of the benefits criteria, a favorable innovation was one that could be expected to provide a reduction in the mean or standard deviation of the runway occupancy time or an increase in the predictability of the runway occupancy. Where a reduction in either the mean or the standard deviation might be accompanied by an increase in the other, the assessment was based on the larger effect anticipated. In the case of requirements for changes in the system, a favorable assessment indicates relatively modest requirements, short implementation time frame, good institutional acceptability or good suitability for retrofit. Conversely, an unfavorable assessment indicates considerable requirements, long implementation time frame, poor institutional acceptability or poor suitability for retrofit. A favorable assessment for side effects indicates that the impact of the innovation is likely to be favorable under that criterion. A neutral assessment indicates that the innovation either has an impact that is neither beneficial nor detrimental, or that the impact is likely to be of relatively small magnitude.

The assessment was performed using professional judgement based on the technical knowledge of the research team members. The results of this assessment are shown in Tables 3.5 - 3.7. The symbols in these tables permit the identification of those innovations that appear to offer promising benefits without excessively heavy system requirements or large adverse side effects.

Table 3.5

Preliminary Evaluation - Aircraft Innovations

	Reduction in mean and variance	Predictability of ROT	Capital cost	Need for new technology	Need for new facilities and equipment	Need for new procedures	Implementation time frame	Institutional acceptability	Suitability for retrofit	Safety impact	Noise impact	Pilot workload	Controller workload	Go-around probability	Aircraft separation	Aircraft fleet mix compatibility	Land requirements	Passenger comfort	Airport impacts
1. Increase deceleration capability																			
a. reverse thrust	O		⊖	O	O	O	⊖	O	⊖	O	⊖	O	O	O		O	O	⊖	O
b. improved braking	O		⊖	O	O	O	⊖	O	⊖	O	O	O	O	O	O	O	O	⊖	O
c. increased drag	O		⊖	O	O	O	⊖	O	⊖	O	O	O	O	O	O	O	O	⊖	O
d. arresting devices	⊖		⊖	O	⊖	O	⊖	⊖	⊖	O	O	⊖	O		O	⊖	O	⊖	⊖
2. Increase exit turn capability																			
a. improved steering and gear	O		⊖	⊖	O	O	⊖	O	⊖	O	O	O	O	O	O	O	O	⊖	O
b. improved tires	O		⊖	⊖	O	O	⊖	O	⊖	O	O	O	O	O	O	O	O	⊖	O
3. Decrease threshold speed																			
a. increased lift coefficient	O		⊖	O	O	O	⊖	O	⊖	O	O	O	O	O	⊖	⊖	O	O	O
b. lower stall speed margin	⊖		O	O	O	O	O	⊖	⊖	⊖	O	⊖	O	⊖	⊖	⊖	O	O	O
c. powered lift	O		⊖	⊖	O	O	⊖	O	⊖	O	⊖	O	O	O	⊖	⊖	O	O	O
d. variable geometry	O		⊖	⊖	O	O	⊖	⊖	⊖	O	O		O	O	⊖	⊖	O	O	O
4. Improve landing aids																			
a. head-up display	⊖	O	⊖	⊖	⊖	O	⊖	O	O	O	O	O	O	O	O	O	O	O	O
b. autoland	O	O	⊖	O	⊖	O	⊖	O	O	O	O	O	O	O	O	⊖	O	O	O
c. NAVSTAR/INS	⊖	O	⊖	⊖	⊖	O	⊖	O	O	O	O	O	O	O	O	O	O	O	O
d. improved pilot view	⊖	O	⊖	O	⊖	O	O	O	⊖	O	O	O	O	O	O	O	O	O	O
e. runway guidance	O	O	⊖	⊖	⊖	O	⊖	O	⊖	O	O	⊖	O	O	O	⊖	O	O	⊖
5. Improve instrumentation																			
a. ground speed	O	⊖	⊖	⊖	⊖	O	⊖	O	O	O	O	O	O	O	O	⊖	O	O	O
b. CDTI	O	⊖	⊖	⊖	⊖	⊖	⊖	O	O	O	O	⊖	O	O	O	⊖	O	O	O
c. ambient condition display	O	O	⊖	⊖	⊖	O	⊖	O	O	O	O	O	O	O	O	⊖	O	O	O
6. Improve go-around performance	O		⊖	⊖	⊖	O	⊖	O	⊖	O		O	O	O	O	O	O	⊖	O
7. Reduce aircraft weight	O		O	O	O	⊖	O	⊖	O	O	O	O	O	O	O	O	O	O	O

Assessment Legend	BENEFITS	CHANGES	SIDE EFFECTS
O	Significant	None	Significant favorable
⊖	None or Minor	Minor	None or Minor
⊖	Significant Adverse	Major	Significant adverse

Table 3.6

Preliminary Evaluation -- Airport Innovations

	Reduction in mean and variance	Predictability of ROT	Capital cost	Need for new technology	Need for new facilities and equipment	Need for new procedures	Implementation time frame	Institutional acceptability	Suitability for retrofit	Safety impact	Noise impact	Pilot workload	Controller workload	Go-around probability	Aircraft separation	Aircraft fleet mix compatibility	Land requirements	Passenger comfort	Airport impacts
1. Locate exits to minimize occupancy	0		θ	0	θ	0	θ	0		0	0	0	0	0	0	0	0	θ	θ
2. Location of runways, taxiways and terminals	0		θ	0	θ	0	θ	0		0	0	0	0	0	0	0	0	0	θ
3. Location of circulation taxiways			θ	0	θ	0	θ	0		0	0	0	0	0	0	0	0	0	θ
4. Optimize width of airfield elements																			
a. runways			θ	0	θ	0	θ	0		0	0	0	0	0	0	0	0	0	θ
b. exits and fillets	0		θ	0	θ	0	θ	0		0	0	0	0	0	0	0	0	0	θ
c. taxiway turns			θ	0	θ	0	θ	0		0	0	0	0	0	0	0	0	0	θ
5. Match exit radii to aircraft performance	0		θ	0	θ	0	θ	0		θ	0	0	0	0	0	0	0	θ	θ
6. Improve exit marking and lighting	θ	0	θ	0	0	0	θ	0		0	0	0	0	0	0	0	0	0	0
7. Improve landing aids																			
a. VASI/approach lights	θ	0	θ	θ	θ	0	θ	0		0	0	0	0	0	0	0	0	0	θ
b. ILS/MLS	θ	0	θ	θ	θ	0	θ	0		0	0	0	0	0	0	θ	0	0	θ
c. pavement marking	θ	0	θ	θ	0	0	0	0		0	0	0	0	0	0	0	0	0	θ
8. Improve runway surface friction	0		θ	0	0	0	θ	0		0	0	0	0	0	0	0	0	θ	0
9. Improve runway entrance location and design	θ		θ	0	0	0	θ	0		θ	0	0	0	0	0	0	0	0	0
10. Additional runways																			
a. close parallel/short parallel	0		θ	0	θ	θ	θ	θ		θ	0	θ	θ	θ	0	0	0	0	θ
b. V-runways	0		θ	0	θ	0	θ	0		θ	0	θ	θ	θ	0	0	0	0	θ
c. variable width/double width	0		θ	θ	θ	θ	θ	θ		θ	0	θ	θ	θ	0	0	0	0	θ
11. Install arrester devices			θ	θ	θ	0	θ	θ		0	0	0	0	0	0	0	0	0	0
12. Aircraft guidance wire in pavement	θ	0	θ	θ	0	0	θ	0		0	0	0	0	0	0	θ	0	0	θ
13. Improve runway safety areas			θ	0	0	0	θ	0		0	0	0	0	0	0	0	θ	0	θ
14. Deceleration gradients																			
a. runways	0		θ	0	0	0	0	0		0	0	0	0	0	0	0	0	0	θ
b. exits	θ		θ	0	0	0	0	0		0	0	0	0	0	0	0	0	0	θ

See Fig. 3.5 for Assessment Legend.

Table 3.7

Preliminary Evaluation - Pilot and ATC/FAR Innovations

	Reduction in mean and variance	Predictability of ROT	Capital cost	Need for new technology	Need for new facilities and equipment	Need for new procedures	Implementation time frame	Institutional acceptability	Suitability for retrofit	Safety impact	Noise impact	Pilot workload	Controller workload	Go-around probability	Aircraft separation	Aircraft fleet mix compatibility	Land requirements	Passenger comfort	Airport impacts
PILOT INNOVATIONS																			
1. Standardize landing and roll-out procedures	◐	O	O	O	O	◐	◐	◐		O	O	O	O	O	O		O	O	O
2. Pilot motivation	O	◐	O	O	O	O	O	O		O	O	O	O	O	O		O	◐	O
3. Remove airline restrictions	◐		O	O	O	◐	O	◐		◐	◐	◐	O	O	O		O	O	O
4. Improve pilot information																			
a. exit location	◐	◐	O	O	O	◐	O	O		O	O	◐	O	O	O		O	O	O
b. environmental conditions	◐	◐	O	O	O	◐	O	O		O	O	◐	O	O	O		O	O	O
ATC/FAR INNOVATIONS																			
1. Permit multiple occupancy																			
a. left-right/short-long	O		O	O	O	◐	O	◐		◐	O	◐	◐	◐	◐		O	O	◐
b. arrivals-departures	O		O	O	O	◐	O	◐		◐	O	◐	◐	◐	O		O	O	◐
2. Enforce exit selection	O	O	O	O	O	◐	O	◐		◐	◐	◐	◐	O	O		O	◐	O
3. Lower threshold height	◐		O	O	◐	◐	◐	◐		◐	◐	◐	◐	◐	O		O	O	O
4. Designate taxiway to local control	◐		O	O	O	◐	O	O		O	O	O	◐	O	O		O	O	◐
5. Sequence aircraft by occupancy characteristics	O		O	O	◐	◐	O	◐			O	O	◐	O			O	O	O
6. Improve controller information																			
a. aircraft speed and acceleration			◐	◐	◐	O	O	O		O	O	◐	O	O	O		O	O	O
b. aircraft characteristics			◐	◐	◐	O	O	O		O	O	◐	O	O	O		O	O	O
c. pilot intentions			◐	◐	◐	O	O	O		O	O	◐	◐	O	◐		O	O	O
7. Automate departure and go-around decisions			◐	◐	◐	◐	O	◐			O	O	O	O			O	O	O
8. Establish approach tolerance limits	◐	O	O	O	O	O	O	◐		O	O	◐	O	◐	O		O	O	O
9. Modify final approach path	◐		O	O	O	O	◐	◐		◐	O	◐	◐	◐	◐		O	O	O

See Fig. 3.5 for Assessment Legend.

Results of the evaluation

Aircraft innovations generally were thought to produce favorable changes in mean and variance of the runway occupancy time, although the benefits of arresting devices were uncertain due to the mass of the aircraft involved, the disengagement problem, and the need to reset the device after each use. Similarly, the benefits of lower stall speed margins and hence slower approach speeds were uncertain due to the trade-off between reduced deceleration times and increased time to touchdown. Three of the improved landing aids (head-up display, NAVSTAR/INS, and improved pilot view) were not expected by themselves to improve runway occupancy parameters significantly. Improved landing aids and improved instrumentation were the only aircraft innovations thought likely to produce favorable changes in the predictability of the runway occupancy, with the benefits of ground speed instrumentation and cockpit display of traffic being somewhat uncertain.

Almost all of the aircraft innovations were thought to require substantial capital investments, with the exception of changes in the stall speed margin and reduced aircraft weight, assuming that the latter is achieved by improved design and component elimination, rather than the introduction of more esoteric materials or sophisticated fabrication techniques. Variable geometry wings, head-up displays, and improved cockpit instrumentation were all thought to require substantial investments in developing the required technology, while arresting devices, improved landing aids (except for improvements in pilot view from the cockpit), improved cockpit instrumentation, and improved go-around performance would all require major expenditures for new facilities and equipment.

Several aircraft innovations would require extended time frames for implementation due to the need to develop the necessary technology, to ensure compatibility between the ground-based and aircraft-based component, or to establish and verify safe operating procedures. Arresting devices, increased lift coefficients, powered lift, variable geometry and improved go-around performance are all innovations that would be largely introduced with new aircraft, and thus limited to the next generation of aircraft. A NAVSTAR-based landing aid would require the deployment and availability of the satellite system upon which it is based. The use of arresting devices and reduced stall speed margins may also run into difficulties of institutional acceptability, particularly due to pilot concerns about safety. Most of the long lead-time technology improvements discussed above would be more suitable for deployment in the next generation of aircraft, and would not generally be suitable for retrofitting to the existing fleet. However, increased lift coefficients could possibly be achieved by wing modifications, and NAVSTAR/INS-based landing aids could be retrofitted as soon as the support technology or satellite systems become available. On the other hand, improving the pilot view from existing cockpits may be very difficult without redesigning the entire cockpit layout.

Adverse safety impacts are likely to be created by lowering stall speed margins or reducing aircraft weight, if this is done by reducing structural component sizes or eliminating redundancy. Increase in the use of reverse thrust would have adverse noise impacts. Arresting devices were thought likely to increase pilot workload. Measures to decrease threshold speed would adversely influence aircraft separation, if capacity is not to be reduced. However, as discussed elsewhere this report, this may not be as important as is conventionally thought. There would be obvious fleet mix compatibility impacts with arresting devices and runway guidance technology if not all aircraft were using the same system, or if some were using the system and some not. Passenger comfort is likely to be adversely affected by the use of arresting devices or increased turn capability due to the higher decelerations involved. There are also likely to be substantial airport impacts created by the use of arresting devices, due to changes in the way departing aircraft are handled and any necessary measures to accommodate the devices themselves.

Airport innovations were generally thought to give favorable changes in the mean and variance of the runway occupancy time, although the improvements to exit marking and lighting, landing aids, and runway guidance were felt to contribute more toward increasing the predictability of runway occupancy than changing the occupancy time parameters. The changes in runway occupancy parameters resulting from improved runway entrance location and design and provision of deceleration gradients at runway exits were not thought to be as favorable.

All airport innovations were considered to involve major or moderate capital costs, with runway exit and entrance location and design, and runway and exit lighting and marking innovations requiring less investment than the other airport innovations. The need for new technology was felt to be largely restricted to variable width runways, arrester devices and runway guidance measures, with some further development required for improved landing aids. A substantial requirement for new facilities and equipment would be created by changes in airfield configuration or relocation of circulation taxiways, by measures to optimize the width of airfield elements or improve approach lighting and electronic landing aids, and by the provision of additional runways or installation of arrester devices. Provision of close parallel, variable width or double width runways would create a need for new procedures. Long implementation time frames could be expected for changes to the airfield configuration, optimization of runway width and provision of additional runways. The introduction of improved ILS/MLS systems may be delayed by the lead time for research and development while improvements in runway surface friction beyond the present capability may have to await a major breakthrough in pavement research. Improvement in runway safety areas may be slow to be implemented because of conflicts with existing airport facilities and layout. It was thought that gaining institutional acceptance may be difficult for close parallel, short parallel (especially when used for intersection takeoffs or stop-short landings) and variable width runways.

Provision of additional runways within the existing airfield configuration was considered likely to generate unfavorable safety and controller impacts and adversely impact go-around probability. The use of close parallel or increased width runways, and to a lesser extent V-runways, is likely to generate adverse aircraft separation impacts in the approach stream.

Aircraft runway guidance with buried wire technology will create aircraft fleet mix compatibility impacts. Relocation of circulation taxiways will have major land requirement impacts. Finally, most of the airport innovations will of course have substantial impacts on the operation of the airports involved, in particular changes in airfield configuration, relocation of circulation taxiways, optimizing the width of airfield elements, matching exit radii to aircraft performance, provision of additional runways within the existing airfield configuration, improvement in runway safety areas and provision of deceleration gradients.

Pilot innovations appeared to produce less obvious benefits and have lower requirements and generate less adverse impacts than the other classes of innovation. Generally, pilot innovations were considered to give modest reductions in the mean and variance of the runway occupancy time and most improvement in runway occupancy predictability. It was felt that pilot motivation might result in more substantial reduction in runway occupancy parameters, while standardizing landing and roll-out procedures could significantly improve predictability of runway occupancy.

No pilot innovations were thought to present major requirements for capital expenditure, new technology, or new facilities and equipment. Standardization of landing and roll-out and removal of airline operating restrictions would establish a need for new procedures, and would probably face difficult tests of institutional acceptability at the hands of both pilots and airlines.

Side effects of the innovations were generally favorable with minor adverse safety, noise, and pilot workload impacts from the removal of airline restrictions. Paradoxically, improving pilot information may also lead to an increase in pilot workload. Increasing pilot motivation may lead to aircraft handling that reduces passenger comfort.

ATC/FAR innovations contribute both to a reduction in the mean variance of the runway occupancy time and to the predictability of the runway occupancy. Permitting multiple runway occupancy would not strictly reduce runway occupancy time of itself, but would permit an increase in capacity for a given runway occupancy time. Enforcing exit selection would increase predictability while reducing both mean runway occupancy time and its variance. Lowering the threshold height and designating portions of the taxiway system to local control would probably give a modest reduction in runway occupancy time due to the reduced airborne time after the threshold and the knowledge of the pilots that if exiting early at a higher speed they will not have to pull up short on entering the taxiway system. Sequencing aircraft by occupancy characteristics appears to offer another way of increasing capacity without necessarily changing runway occupancy in the technical sense. Improvements in controller information would increase the predictability of runway occupancy times. The automation of departure or go-around decisions is another innovation that achieves a capacity increase without changing any of the strictly-defined runway occupancy parameters. The establishment of approach tolerance limits for flight path and airspeed was thought to significantly enhance the predictability of the runway occupancy, with some modest reduction in the mean and variance of the occupancy time as pilots try harder to fly a precise approach and have an external criterion to measure their performance. Modification of final approach path was felt to offer a modest reduction in runway occupancy parameters due to change in the airborne time from threshold to touchdown.

Most of the innovations are primarily procedural and heavy capital costs are not involved. Some capital investment may be needed to support better controller information or decision automation. The automation of the departure/go-around decision was felt to require substantial new technology. Lowering the threshold height may create a strong need for new facilities and equipment funds, especially to replace landing aids or to lower approach lighting. Permitting multiple runway occupancy, the enforcement of exit selection, and sequencing aircraft by runway occupancy characteristics present a clear requirement for new procedures. Multiple runway occupancy, enforced exit selection, lower threshold height and modifications to the final approach path were all thought likely to encounter problems of institutional acceptability, on grounds of safety.

In fact, multiple runway occupancy and lower threshold height were the only innovations that were thought to have major adverse safety impacts, with minor concern from the safety impacts of enforced exit selection and modification to the final approach path. Multiple runway occupancy and enforced exit selection appeared to have significant adverse pilot and controller workload problems. Lower threshold height and approach tolerance limits would also generate adverse pilot workload. Designation of a taxiway to local control and the establishment of approach tolerance limits were considered to adversely impact controller workload. Go-around probability would be increased by multiple runway occupancy, the implementation of approach tolerance limits, and modifications to the final approach path, which were also thought to have significant aircraft separation impacts.

INTERACTION BETWEEN THE INNOVATIONS

Thus far, each of the innovations has been considered as an independent action that might be taken to reduce runway occupancy time, or reduce the constraint of runway occupancy on capacity, except that the use of arresting devices or runway guidance equipment as an aircraft innovation implies the installation of the ground part of the system as an airport innovation.

However, it is unlikely that any program to improve runway occupancy characteristics would be restricted to only one innovation. Certain innovations when implemented in combination, may give a greater payoff than the sum of their individual effects. Some innovations may only give useful results in conjunction with other innovations. On the other hand, some innovations are mutually exclusive, while some combinations produce benefits by changing the same factors. These benefits cannot be obtained more than once, thus the benefits of one may preclude any further benefits from another. With multiple combinations of innovations, there may also be interference effects that increase the magnitude of any adverse impacts or reduce the benefits received.

A number of combinations of two innovations are identified in Tables 3.8 and 3.9. In most cases the advantages to be gained from the combinations, or the necessity of implementing the innovations together, is reasonably self-evident.

Further reasons for considering the interaction of innovations lie in the implementation process. The implementation of a specific innovation may depend on actions being taken on other innovations, while

Table 3.8

Innovation Combinations Requiring Joint Implementation to Achieve Benefits

Clearance to circulation taxiways	/	Design exits for increased speed
Standardize landing and roll-out	/	Remove airline restrictions
Enforce exit selection	/	Designate taxiway to local control
Aircraft arresting devices	/	Install airport arresting devices
Increase exit turn capability	/	Clearance to circulation taxiways
Aircraft runway guidance aid	/	Guidance wire in pavement
Design exits for increased speed	/	Designate taxiway to local control
Variable/double width runway	/	Permit multiple occupancy

Table 3.9

Innovation Combinations Likely to Improve the Benefits When Implemented Jointly

Variable/double width runway	/	Improve runway safety areas
Pilot motivation	/	Improve pilot information
Permit multiple occupancy	/	Improve controler information
Permit multiple occupancy	/	Automate departure/go-around decision
Enforce exit selection	/	Sequence aircraft
Sequence aircraft	/	Improve controller information
Improve braking capability	/	Improve runway surface friction
Increase exit-turn capability	/	Locate exits to match fleet
Improve go-around performance	/	Automate departure/go-around decision
Locate exits to match fleet	/	Enforce exit location

different innovations require actions by different sectors of the industry. In some cases, the implementation of a single innovation may require coordination and action from several sectors in order to proceed. This coordination may be easier to achieve in the context of considering a wide-ranging set of strategies. In order to evaluate these alternative strategies, and to reduce the evaluation to manageable proportions, the innovations need to be grouped into coherent packages.

4. INNOVATION PACKAGES

The previous chapter identifies a large number of innovations that were generated by a "brainstorming" process influenced by the knowledge and information available at the early stages of the research. A preliminary evaluation resulted in directly putting aside some of these whose feasibility could not be ascertained without extensive analyses and additional information. It was found that many of the innovations interact and can be grouped into what are termed packages of innovations. This chapter describes six selected packages that were developed and evaluated.

DEVELOPMENT OF SELECTED PACKAGES OF INNOVATIONS

The packages of innovations, or programs to reduce runway occupancy times and their effects on capacity, were developed on the basis of the similarities and interactions between the individual innovations.

The first package was assembled because of the recognition that much can be achieved by changes in aircraft technology. Given that the opportunities for any significant changes in conventional jet aircraft technology are rather limited for the medium and long haul jet fleet (since most of the aircraft that will make up this fleet within the next 20 years are either flying today or already in the production stage), we have concentrated on short haul aircraft technology and identified a package of innovations that could be built into new aircraft developed specifically for short haul, or for low density markets. The emerging new role of commuter airlines, and the potential increase in demand for such aircraft, may make such technological development feasible. The opportunity to include some of these innovations in such a development is still at hand.

The next two packages of innovations were motivated by discussions with pilots. They were also suggested by the wide variation observed in the landing process, even under similar conditions, implying that pilots have considerable discretion in determining the landing process. One package deals with means of motivating pilots and airlines to consistently reduce occupancy times to the extent possible, and the other package deals with improving information flow to both pilots and controllers. Improved information can be thought of almost as a prerequisite for achieving the occupancy time reductions that can be made possible with other innovations.

Two additional packages were developed to respond to the impact of runway design and airport configuration. The data reviewed suggested that exit location continues to be an important factor, as does exit design. Innovative ways to redesign the airfield surface in order to permit, or to support, changed aircraft performance and landing procedures become then an obvious candidate for consideration.

Finally, the need to look at runway occupancy as part of an integrated process that encompasses the final approach path as well as the runway itself led to the development of a package termed Integrated Landing Management. This package deals with means of achieving consistency between time headways of aircraft on final approach and runway occupancy times on the runway.

Each of these packages is discussed below. As is discussed later in this chapter, these packages are not necessarily independent and there may be benefits from combining them into larger programs.

DESCRIPTION AND EVALUATION OF INNOVATION PACKAGES

This section describes in detail the composition of each of the six selected innovation packages and the results of the evaluation of the benefits that may be expected from each, together with a consideration of the implementation requirements and the associated impacts.

It was felt to be beyond the scope of this report to attempt to apply a more detailed evaluation methodology to the wide range of innovations identified below than that described in Chapter 3. The benefits of a specific package are assessed in terms of the percentage increase in runway capacity that can be attributed to the innovations, either through a reduction in runway occupancy time or otherwise, under specified baseline conditions.

The computation of the changes in runway occupancy time as a result of a specific innovation were performed with the aid of a computer program that modelled the approach and landing path of an aircraft as a function of its performance parameters. These parameters were changed to reflect the different innovations. In both the baseline condition and the real world, the location of runway exits influences the runway occupancy times due to the stochastic nature of the aircraft performance. Even if on average all aircraft of a particular type decelerate quickly enough to take a given exit, in reality there will always be some that miss the exit and incur a much longer runway occupancy while they taxi to the next available exit. The computer program modelled this stochastic variation by simulating a sequence of landings with the parameters having the same mean value, modified by a random component to reflect the variation in aircraft performance encountered in practice.

IMPROVED SHORT-HAUL AIRCRAFT TECHNOLOGY

<u>Objective</u>

Improved aircraft performance during landing and take-off offers one strategy to reduce runway occupancy. This performance improvement can be achieved through technology designed into new aircraft, or retro-fitted to existing aircraft. Some changes in the existing technology may require corresponding changes in other parts of the system, such as the runway surface. The objectives of these technological improvements consist of:

- Increased deceleration on landing or acceleration on take-off.
- Increased turn capability in order to exit at higher speed.
- Reduced touchdown or lift-off speed in order to reduce the amount of deceleration or acceleration required on the runway.
- Improved go-around performance to permit controllers to delay go-around decisions in marginal cases.

Increased deceleration or exit speed will only result in a reduction in runway occupancy time if the aircraft is in fact able to exit on reaching exit speed. This implies that the benefits of these improvements will only be realized if runway exits are currently being passed up by landing aircraft, or if new exits are provided.

Technology changes to achieve these objectives are likely to create a weight penalty when compared with existing technology, or future technology designed for the current environment. The magnitude of this penalty will increase with stage length, hence these changes are likely to offer the biggest pay-off for short-haul aircraft. Another reason for concentrating on short-haul aircraft is that reduced runway occupancy times generally translate into reduced runway length requirements, increasing the possibilities of providing separate short-haul runways at busy airports.

Enhanced runway deceleration and acceleration

Aircraft improvements to increase deceleration on the runway include:

- Increased reverse thrust
- Improved brakes and tires to permit higher sustained braking
- Measures to increase the aerodynamic drag during landing.

Increased thrust-to-weight ratios will also improve acceleration on take-off and go-around performance.

Since runway friction is currently a limiting factor in braking under some circumstances, improvements in runway surface friction may be required to match improved brakes and tires.

Enhanced exit turn capability

Improvements in aircraft steering and landing gear to tolerate higher side forces will permit pilots to exit at higher speeds. These improvements must address the structural integrity of the gear and the ability of the tire to both withstand the higher side forces involved and to develop sufficient friction at the tire/runway interface to transmit these side forces to the runway. A major problem arises with nose wheel tire scrub. However there are other ways to provide the necessary steering forces such as aerodynamic control or asymmetric power. Active control integration could provide real-time adjustment of rudder, power and nose wheel castor to optimize steering control.

As with braking improvements, improved tire technology to withstand higher side forces may require improvements in runway surface friction.

Reduced touchdown and lift-off speeds

Reduction in touchdown speed will reduce the time spent decelerating to exit speed from touchdown for a given deceleration capability. However, for a given approach path (defined by the glide slope and glide path height over threshold), the time from threshold to touchdown will be increased by a reduction in approach speed. There are also capacity implications of a reduction in approach speed for a given minimum distance separation on approach, as noted elsewhere in this report. Maintaining higher approach speeds then bleeding off excess airspeed prior to touchdown will move the touchdown point down the runway and result in increased time between threshold and touchdown. Thus measures to reduce touchdown speed should be made in the context of either accepting reduced distance separation on approach, in order to maintain headways at lower approach speeds, or of providing enhanced airborne deceleration capability.

Reduction in touchdown and approach speeds can be achieved by:

- Increasing the lift coefficient in the landing configuration
- Reducing the stall speed through the provision of powered lift
- Increasing the wing area through variable geometry technology.

All three measures will require increased power, either to combat increased drag or to provide powered lift.

Reduction in the time from threshold to touchdown can be achieved by:

- Reducing the margin of approach speed over stall speed in approach configuration
- Use of reverse thrust prior to touchdown
- Increased aerodynamic drag.

Reducing the stall speed margin has obvious safety implications, and may require active controls linking flight controls and power or airbrake settings to airspeed, in order to prevent an inadvertent stall while the pilot's attention is distracted. The use by Concorde of a lower margin suggests that the safety concern is not insurmountable. Use of airborne reverse thrust may have flight stability implications, although it has been used successfully in some military aircraft.

Improved go-around performance

Increased thrust-to-weight ratios have already been discussed above. Another factor in determining go-around performance is the time required for turbine engines to develop to full power. If this could be reduced, then the lag between the go-around decision and the aircraft initiating a climb could also be reduced. Finally, a rapid reduction in aerodynamic drag without a corresponding reduction in lift would permit faster aircraft acceleration or earlier climb initiation. An active airspeed/flight control system as discussed above may permit climb initiation at the earliest moment.

Evaluation

The above measures achieve a reduction in runway occupancy time either by directly reducing the time spent between threshold and exit or by permitting controllers some discretion in overlapping successive runway occupancies by allowing a following aircraft to proceed beyond the threshold in marginal cases before ordering a go-around. Several of the improvements identified above contribute to more than one way of reducing the runway occupancy time, thus improved tires and runway surface friction under some circumstances will allow both increased braking and higher exit speeds. Some improvements have no obvious upper bound (such as how much increased drag is feasible). This suggests an evaluation strategy that considers the following aspects of runway occupancy time:

- Time from threshold to touchdown
- Time from touchdown to exit

- Buffer needed to prevent excessive go-arounds.

For a one second reduction in each of these aspects, the benefits resulting from the consequent capacity increase can be assessed. These benefits can then be compared with the costs of achieving a progressively increased performance using the following independent strategies:

- a) Increased thrust-to-weight ratio with rapid engine wind-up.
- b) Enhanced braking using improved brakes, tires and runway surface friction.
- c) Enhanced exit turn capability with improved landing gear, tires, runway surface friction and active control integration.
- d) Increased aerodynamic drag with compensating power on approach and airborne reverse thrust before touchdown.
- e) Reduced approach and touchdown speeds using STOL-technology (high lift coefficient, powered lift, variable geometry).
- f) Reduction of stall margin on approach or go-around using active controls .

Further improvement may be obtained from a combination of these strategies.

<u>Benefits.</u> It was assumed that the foregoing strategies could achieve the following improvements in aircraft performance, compared to the baseline case:

- An increase in runway deceleration to 6-10 ft/sec^2

- An increase in exit turn capability to 40-60 knots
- An increase in airborne deceleration to 2-4 ft/sec^2
- A reduction in threshold speed to 120 knots.

Analysis of the effect of these performance improvements on the baseline conditions gave a reduction in runway occupancy time from 5 to 25 seconds. Such a reduction would produce up to an 8% improvement in runway capacity at a typical airport with a typical prevailing aircraft fleet mix. Reducing the runway occupancy time through the foregoing measures also reduces the landing distance required, increasing the potential for independent use of intersecting runways.

Costs. Capital costs associated with these measures are likely to be high, with extensive requirements for aircraft fleet replacement or retrofit. There is also likely to be substantial operating cost penalties resulting from the additional weight associated with the measures to achieve the enhanced performance. Estimates of the dollar values of these costs were beyond the scope of this study. The need to develop the necessary short-haul aircraft technology will require a major research and development program. Tne implementation costs, apart from aircraft retrofit or acquisition, are likely to be moderate, with a limited amount of associated airport improvements, such as improved runway friction courses.

Impacts. The enhanced operating performance may possibly lead to some reduction of safety margins, although some counter-measures (such as the use of active controls) might be able to offset this effect. There is likely to be a moderate increase in aircraft noise resulting from the use of higher engine thrust. The enhanced performance may also lead to some increase in pilot workload due to the reduced reaction time. No significant change is expected in controller workload. While the higher deceleration and exit speeds might be expected to result in some reduction in passenger comfort, the values involved appear to lie within the tolerable range suggested by existing empirical work (e.g. Horonjeff: 1958).

Other considerations. Many of the measures proposed are likely to have a long lead time for implementation and be difficult to retrofit to the existing fleet. There does not appear to be any compatibility problem with the existing aircraft fleet or airports. The benefits increase incrementally with the introduction of the new technology aircraft into the fleet, giving low initial benefits and slow build-up. The benefits occur primarily at busy airports but the capital and operating costs are incurred whenever the advanced technology aircraft are used, on flights between any airports. Thus the cost-effectiveness of these aircraft will be higher if they are primarily used between busy airports and lower if they make many of their flights to relatively uncongested airports.

PILOT AND AIRLINE MOTIVATION AND REGULATION

The empirical evidence available suggests that variation in pilot behavior plays a major role determining the runway occupancy times of landing aircraft. Some studies have concluded that pilot behavior is the most important factor influencing the variation in these times. There is evidence that suggests that enhanced pilot and airline motivation to reduce runway occupancy times is a reasonable course of action. One piece of evidence is the significant variation of runway occupancy time for the same aircraft type under similar conditions. Evidence suggests, for example, that the location of the terminal gates of a particular airline influences the exit selected by pilots of that airline. When the appropriate exit is relatively close to the runway threshold, then shorter runway occupancy times can be observed. This implies that variation in the operating parameters of a given aircraft on a runway are quite possible. In addition, there are rather wide variations in such parameters as approach speed, deceleration rate, touchdown point and height over the threshold. The data suggest that there is no significant direct relationship between these parameters and such environmental factors as wind and temperature, nor does there seem to be a significant difference between aircraft types (See for example, Steuart and Gray: 1981). Runway occupancy times appear to vary most significantly on the basis of the exit used on any given runway; and even for the same exit there remain some variations in runway occupancy times between aircraft. Figures 4.1 - 4.4 illustrate this result for a sample of operations at Atlanta's Hartsfield International Airport. Not only do these figures illustrate the wide variability of some parameters of the landing process, but they also show the absence of any correlations between them and runway occupancy times. While these limited data do not justify any firm conclusion, they do suggest that human factors such as pilot behavior, and airline policy influences do play an important role. This phenomenon is demonstrated by data for Los Angeles Airport reported by Koenig (1978). Landing runway occupancy times for two runways were stratified among two carriers, TWA and UAL. For two runways, 25R and 25L, the results show significant differences in mean occupancy times, as shown in Table 4.1. The consistent difference between these

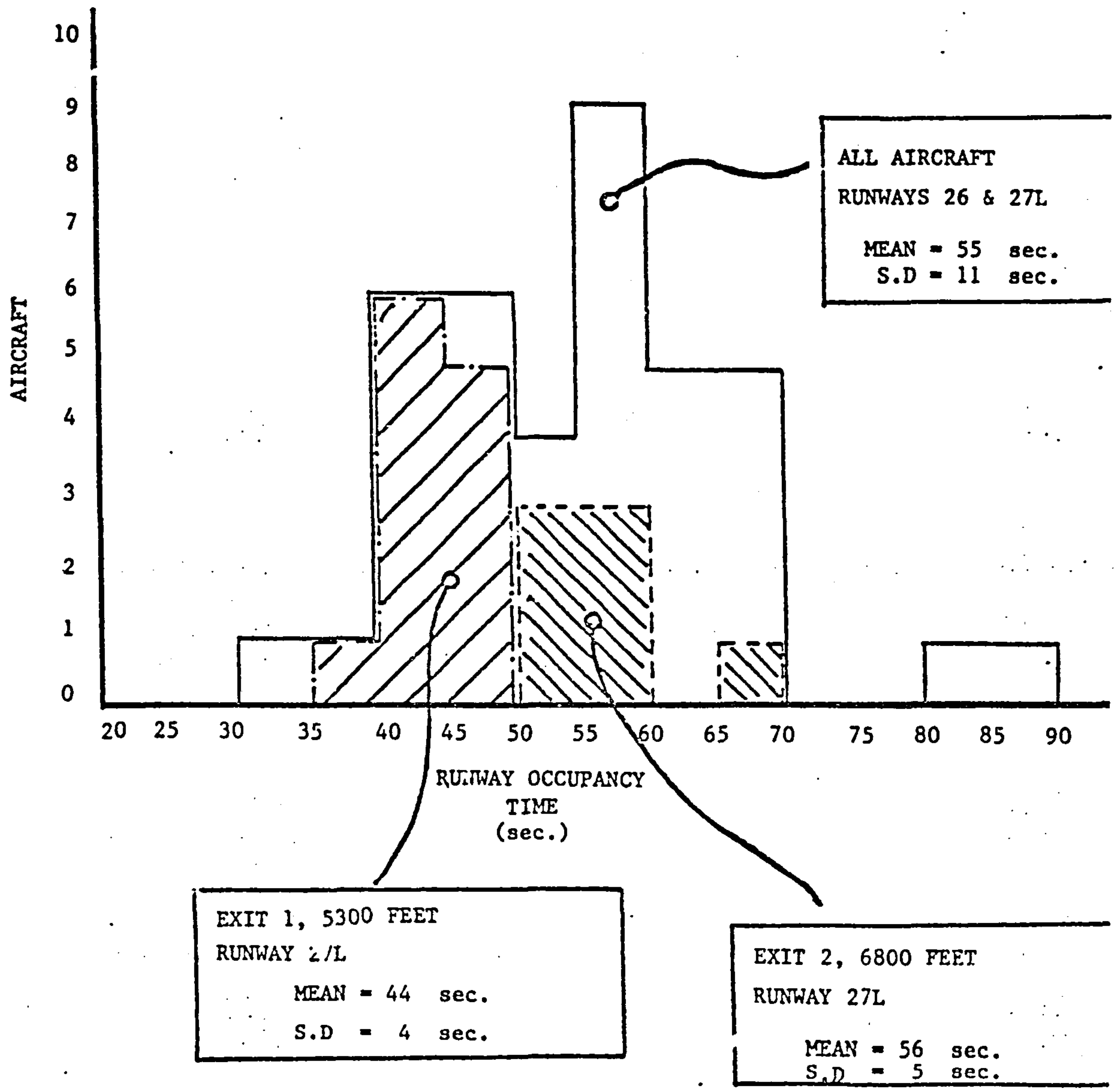
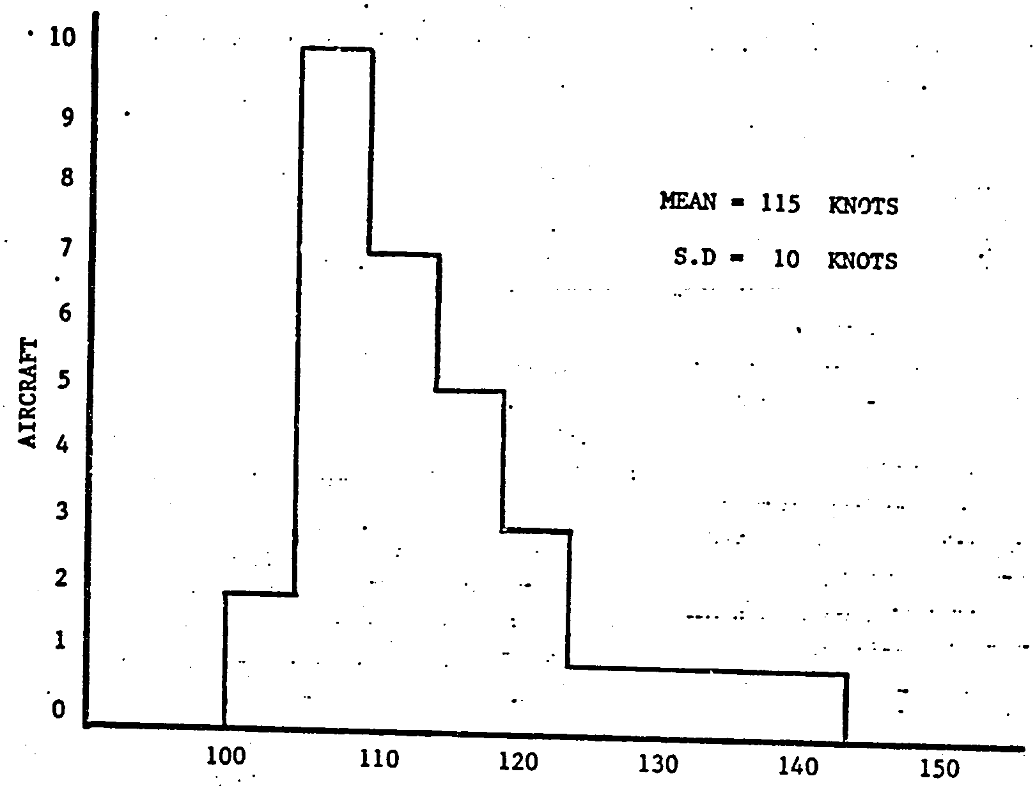
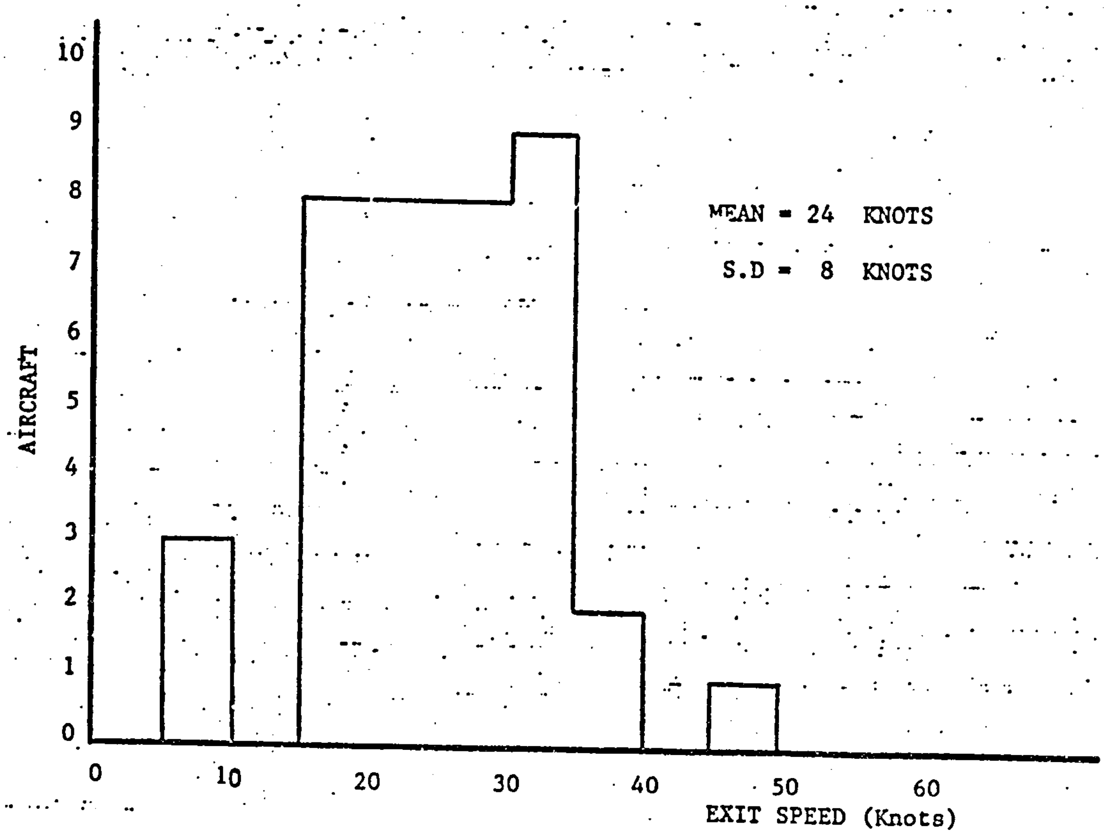


FIG. 4.1 Variation of Runway Occupancy Time with Exit Used--Atlanta.

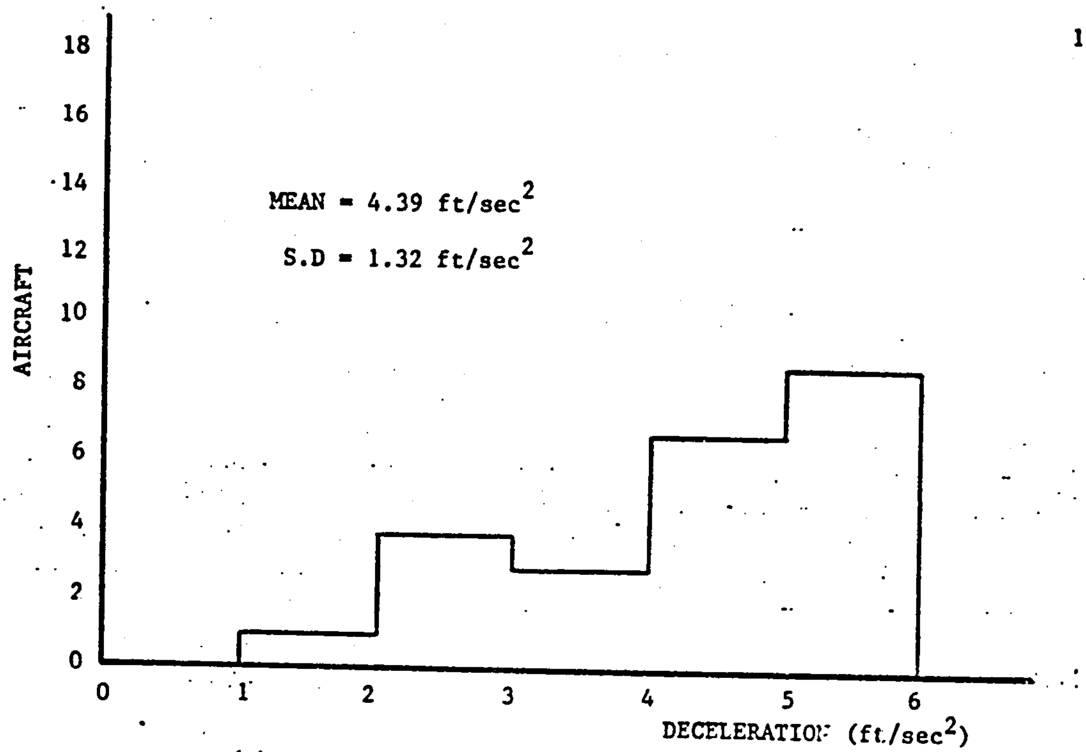


(a) Distribution of Speed Over Threshold

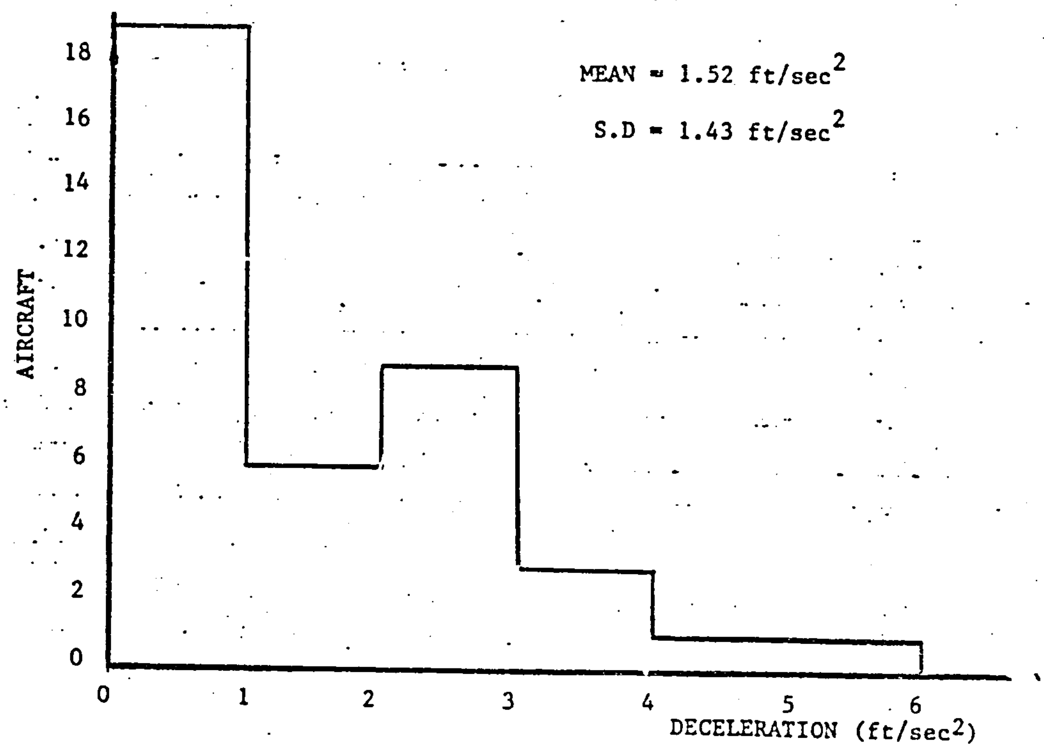


(b) Distribution of Exit Speed

FIG. 4.2 Distribution of Threshold and Exit Speed.



(a) Distribution of Deceleration Rate at 2000 Feet



(b) Distribution of Deceleration Rate at Exit Point

FIG. 4.3 Distribution of Deceleration Rates.

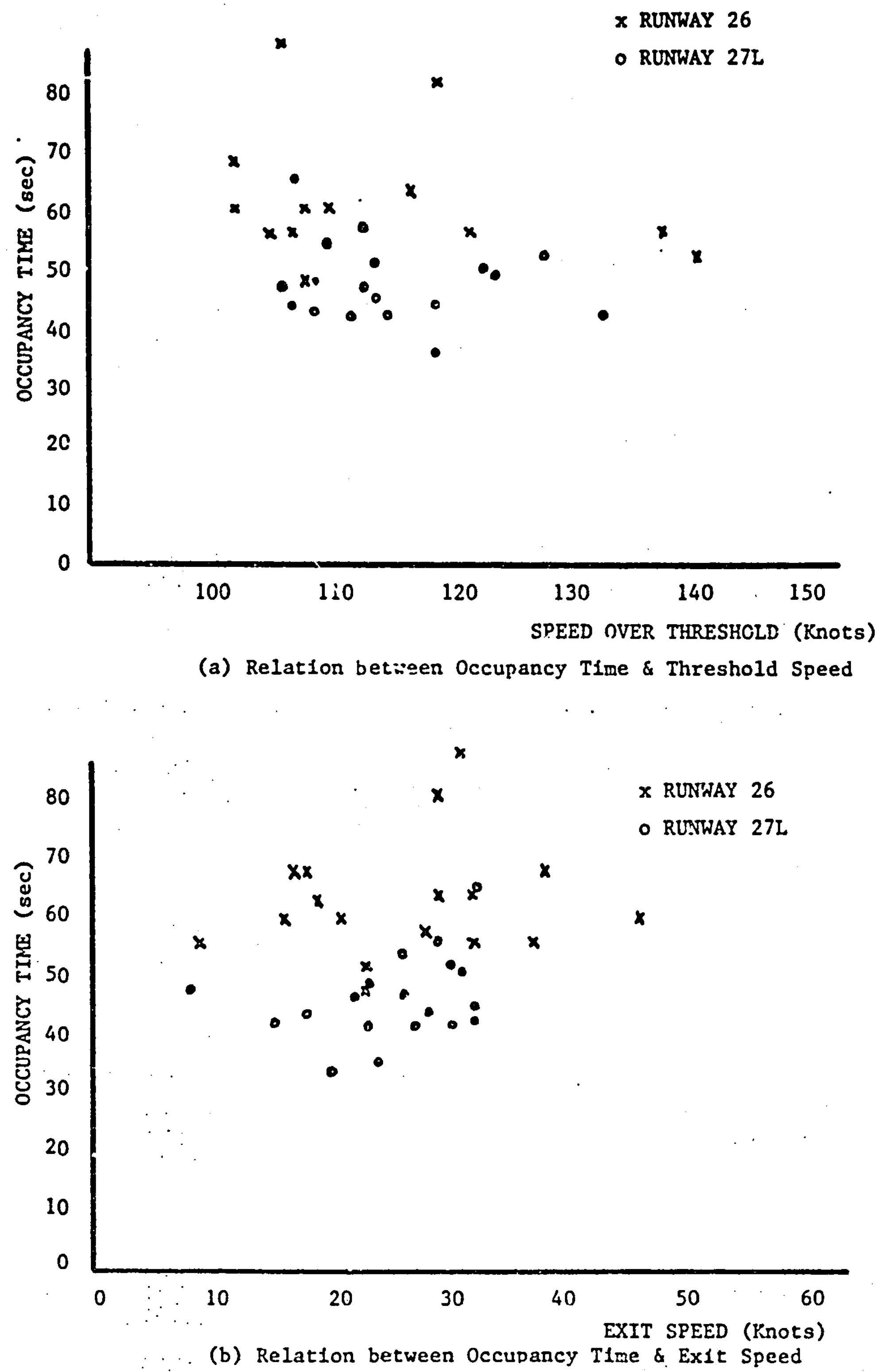


FIG. 4.4 Relation between Occupancy Time and Threshold and Exit Speeds.

Table 4.1

Mean Runway Occupancy Times for Landing Aircraft
Los Angeles International Airport
(seconds)

Runway	Heavy Aircraft UAL	Heavy Aircraft TWA	Light Aircraft UAL	Light Aircraft TWA
25L	50.9	53.3	44.8	51.9
25R	56.8	64.0	52.6	61.5

Source: M.L.Schoen <u>et al</u> [1979]

occupancy times may be explained by the fact that UAL has its terminal nearer to the thresholds of runways 25R and 25L than TWA. Again, the extent to which these differences can be generalized cannot be determined. But the sense is that, in addition to empirical evidence such as the Los Angeles Airport example, the case for pilot motivation and airline policy influences is compelling. Some airlines have explicit policies regarding the application of thrust reversers and aircraft turn maneuvers at given speeds. These policies influence runway occupancy times.

The empirical evidence on hand also suggests that aircraft are capable of landing within a rather wide envelope of parameters. For example, ground speeds over the threshold vary between 105 and 145 knots in the data shown in Figure 4.2. The same can be said for deceleration rates, threshold ground speeds, and exit speeds; all important determinants of runway occupancy times.

In addition to suggesting the importance of pilot and airline behavior in determining runway occupancy times, this is an encouraging result for those interested in reducing those times. It implies that there are possibilities for optimizing aircraft operations on the runway, and that some improvement might be possible within the limits of capability of current aircraft technology. If an aircraft is capable of touching down at 110 knots and at 150 knots as suggested by the Boeing 727 simulations results in Figure 4.5, then one might be able to take advantage of such a wide range of capabilities by varying speeds, headways, and separations in order to optimize the utilization of a runway. Part of this variability in speed is due to variations in the prevailing

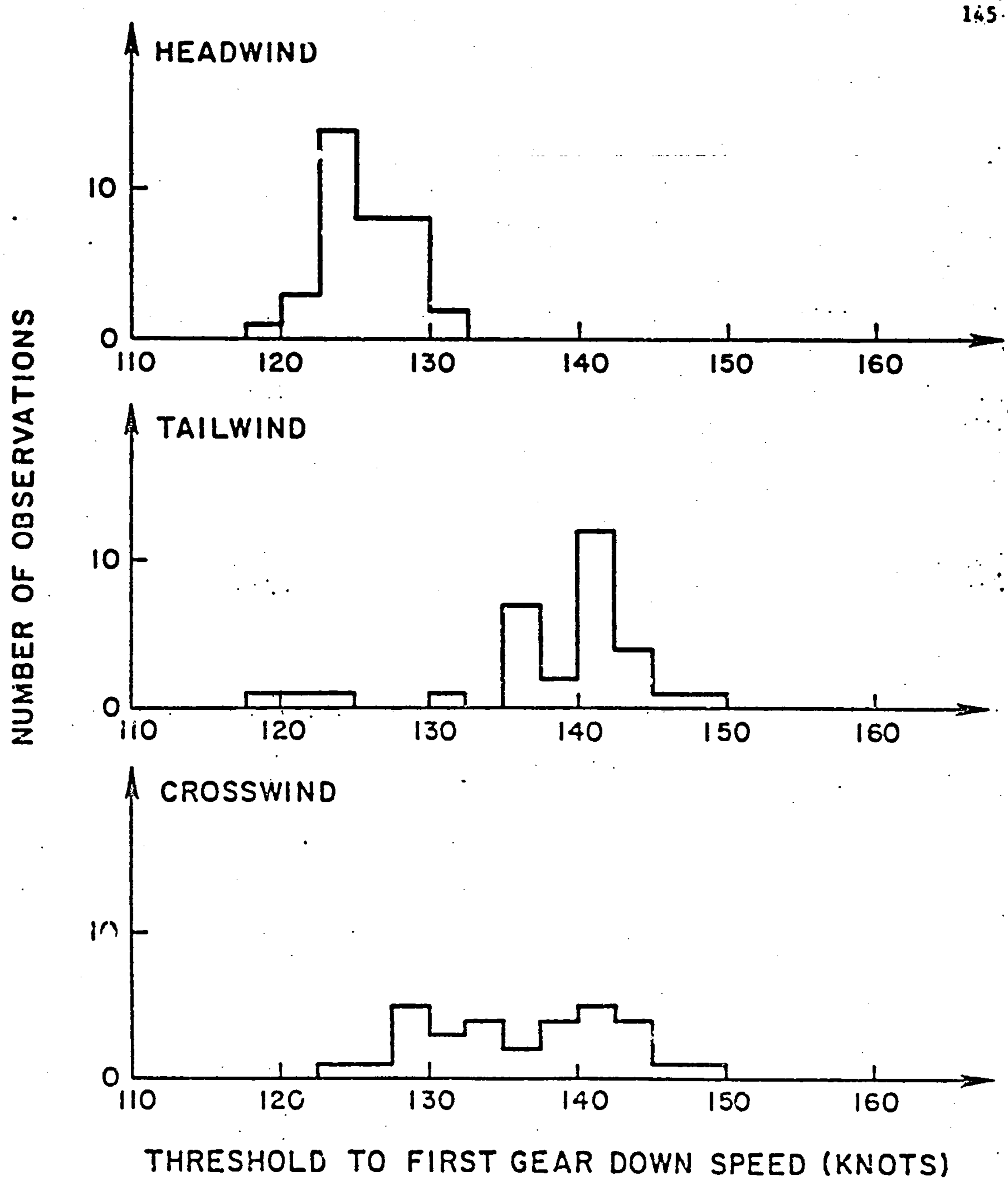


FIG. 4.5 Histograms of Average Groundspeed from Threshold to First Gear Down, based on B-727 Simulator Tests at NASA Ames.

wind. It is most likely that high ground speeds occur in conditions of tail wind, or of little or no headwind. Thus some of these high speeds may not be achievable in other environmental conditions. The same would be true of the opposite case where low ground speeds are observed. Only a detailed analysis of available data would permit the determination of appropriate ranges to use in the context of this discussion. Naturally, a much more thorough investigation of aircraft capabilities, under various operating conditions would be necessary before one goes too far in planning such strategies.

Approaches to Pilot and Airline Motivation

Notwithstanding the stochastic nature of the process of landing an aircraft, it can be said that there is, for any given set of conditions, an optimal path for every aircraft that minimizes the total service time for that landing. If runway occupancy time is the constraining factor on this service time, the optimal path is the one that minimizes the runway occupancy time. This optimal path can be achieved by regulation or by encouraging airlines to establish the appropriate procedures, and pilots to apply them. Neither of these two extremes is appropriate. The first is unrealistic for a number of reasons, not the least important of which is the fact that the landing process is replete with random elements and occurrences that are often outside the control of the pilot or the controller. No amount of regulation will ensure that the optimal landing paths will always be followed by all aircraft. The second view fails for essentially the same reason. It is not sufficient to just encourage pilots to try to reduce runway occupancy time. For any real gains to be made it would be important to virtually eliminate the excessively long occupancies even if the mean is not greatly reduced. To do this would require incentives that are sufficiently strong or alternatively strict regulations and control.

The distinction between pilot and airline motivation is worthy of some consideration before addressing the specific means of such motivation. It can be said that this distinction is redundant since pilots work for airlines, and presumably follow airline policies in their behavior during a landing process. To the extent that all aspects of the landing process are covered by specific airline policy, one need only address the airline. However, there will probably remain a number of factors affecting the overall performance of a landing operation that are at the complete discretion of the pilot, and for which direct pilot motivation may be useful. We shall therefore address the various means of "airline and pilot motivation" as a single set of strategies aimed at these "users" of the runway system. We can identify two major classes of strategies for achieving the desirable parameters of the landing process. The objective of these strategies would be to move toward an optimal landing process through a set of motivating factors. Benefits gained from motivating pilots and airlines to simply reduce runway occupancy times may not be worthwhile, if they do not achieve the "optimal" profile for each landing. As discussed earlier in this report, reducing runway occupancy time is not as important as matching that time with the headway between aircraft, and then reducing both. On the other hand, some benefits can always be achieved by motivating pilots and airlines to reduce runway occupancy times during mixed operations in poor weather conditions. Two classes of strategies are discussed below, namely economic incentives and operational rules.

Economic incentives

Pricing the use of the runway system is probably the only way in which airlines and pilots can be economically motivated to reduce runway occupancy times. Pricing may be better described as a deterrent than an incentive. However, the implementation of a pricing strategy in which the fee for using the runway depends on the runway occupancy time would constitute a strong incentive to airlines to reduce that time. Much of what an airline, or a pilot can do to reduce occupancy time, such as using higher deceleration rates or higher turning speeds, may result in higher aircraft operating costs. For this reason the current tendency is toward longer occupancy times, except perhaps in the case where the airline is motivated by the location of the terminal vis-a-vis the exits available on a runway. With a pricing function that is an increasing function of runway occupancy time, the airline will be faced with two opposing influences. This is illustrated in Figure 4.6 in which schematic cost and price functions are shown. The aircraft operating cost function is likely to show a sharp rise in operating cost as the runway occupancy time decreases. The total landing cost, which is the sum of the two, will have a minimum somewhere in the middle, since both functions are likely to be convex. Airlines using the runway will presumably try to achieve this minimum, if it is physically possible. This will mean a reduction in occupancy time, since in the absence of a time based landing fee, the airline is likely to reduce operating costs by not applying the costly procedures that reduce occupancy time. Runway occupancy time would decrease from some value indicated by t on Figure 4.6 toward the lower value t'. The incentive to reduce runway occupancy time is not only due to the pricing function that may be applied;

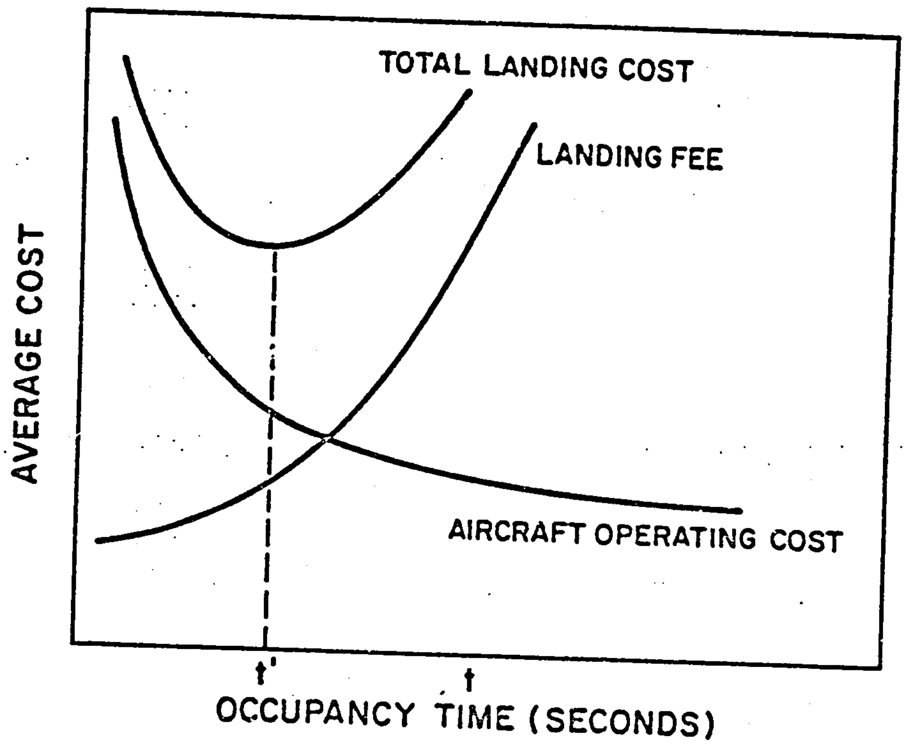
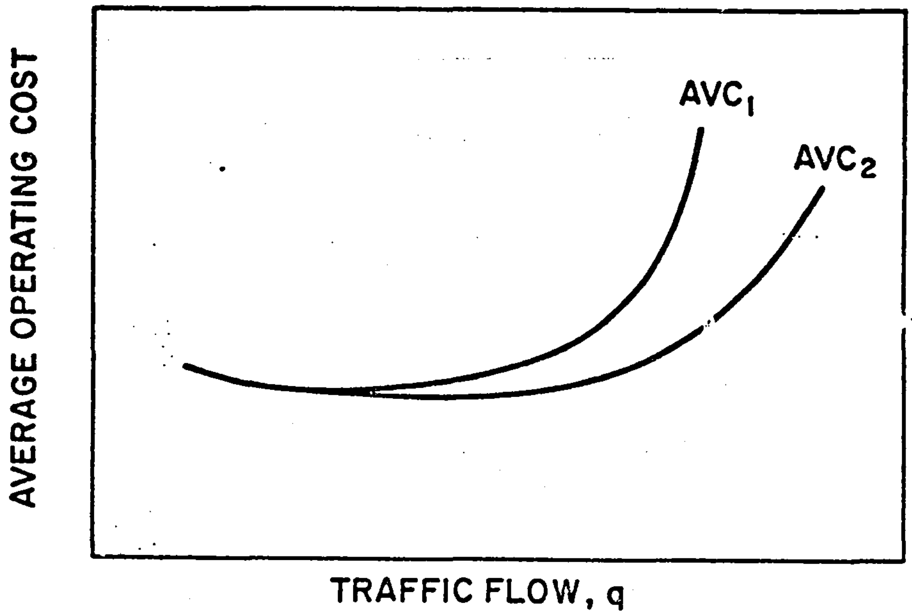


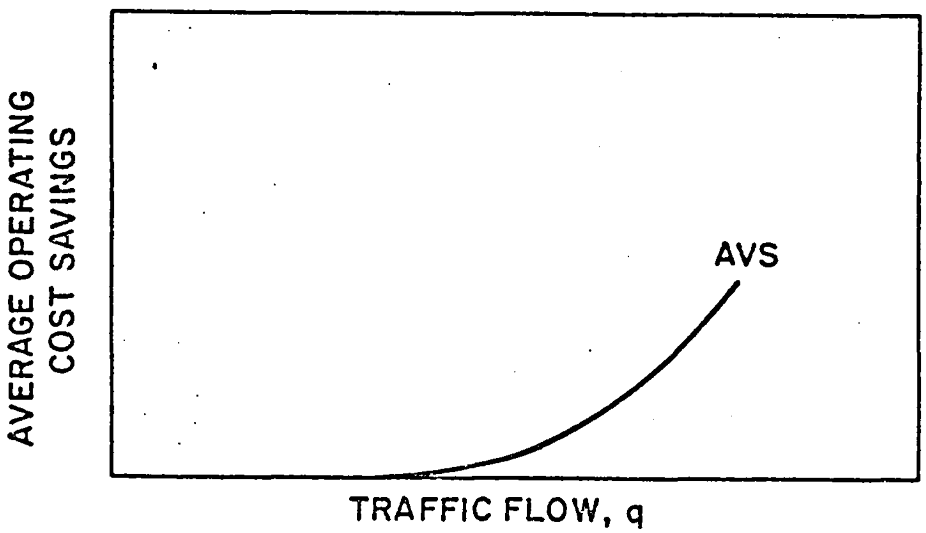
FIG. 4.6 Influence of an Occupancy-based Landing Fee on Total Landing Cost.

during periods of heavy traffic, it is to the advantage of all users to reduce the occupancy time in order to increase the capacity of the runway and reduce delays and aircraft operating costs.

The implementation of a service time based user charging system has profound economic implications, and cannot be done without a thorough analysis. The fundamental rationale behind it is that runway time is a scarce resource that is to be allocated to a number of users, whose use in turn generates benefits. It is clear that such a system will only make sense during periods when runway occupancy time is in fact a capacity constraint, and when traffic is heavy. It would make little sense to charge a progressive landing fee based on runway occupancy time for a landing when there is no other operation immediately following. Therefore pricing on the basis of occupancy time would be implemented during periods of congestion, when the average cost curve for using the runway is rising with traffic volume. The pricing mechanism could be then developed on the basis of recouping the potential benefits from runway occupancy time reduction that would be forfeited if the time is longer than the optimal. To illustrate this we consider the cost functions shown in Figure 4.7(a). These functions show the typical increase with traffic volume, indicating the onset of congestion as volume approaches capacity. Curve AVC_1 represents what might be considered a runway with no "incentives" and with long runway occupancy times. Curve AVC_2 represents the potential cost function if runway occupancy times are optimized for all operations. It is to be noted that the potential benefits from occupancy time reductions increase with traffic volume. These savings are shown in Figure 4.7(b). The objective of the service time based pricing scheme would be lost with longer runway occupancy



(a)



(b)

FIG. 4.7 Effect of Traffic Volume on Average Operating Cost for a Runway.

times. The specific pricing 'scale' to be applied to a runway will also depend on the traffic level at any point in time. With a low traffic volume the penalty for longer occupancy time would be comparatively less than with higher volume, and will increase rapidly as the volume approaches capacity. To see this we can look at Figure 4.8 in which possible contours of equal average delay are sketched for different combinations of traffic flow (q), and occupancy time (t). The convex contour lines illustrate the fact that with a lower occupancy time per operation, a larger number of operations can be accommodated during any given time period.

The practical implications of occupancy time pricing cannot be ignored. There are a number of considerations that have to be dealt with in any analysis of this concept, including the logistics involved in establishing and applying the pricing mechanism. The process would involve the timing of each landing operation in order to determine its occupancy time and matching that information with the flight information for accounting purposes. A number of political issues may have to be resolved before such a concept could be implemented. It may be necessary to demonstrate that this pricing method optimizes the utilization of existing airport facilities, both from the airport and airline perspectives, and from the more general economic efficiency perspective. It may be argued that pricing on the basis of runway occupancy time can only be justified if the optimal landing path for each aircraft is known. This innovation may therefore have to be combined with others discussed in this study, such as improved information flow between airport and aircraft, and the Integrated Landing Management concept.

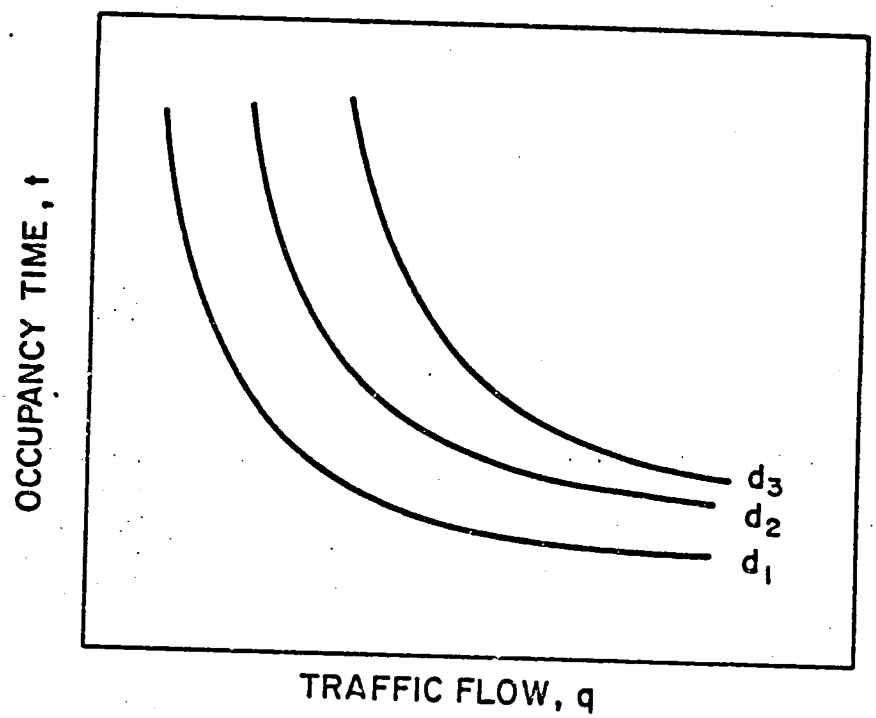


FIG. 4.8 Relationship between Traffic Volume and Occupancy Time for Constant Average Delay.

<u>Regulations and controls</u>

Pricing is not the only form of pilot and airline motivation that can be applied to the current problem. A more direct, although less obviously economically justifiable, method is to institute a set of regulations and controls that will ensure that a prescribed landing path is followed as closely as practicable by every aircraft. This would involve defining the parameters of an optimal landing path and determining their values for a whole range of conditions. Then the appropriate rules and procedures would have to be modified so that the established air traffic control, runway operation, and flight rules all would direct the operation of landing towards the optimal landing paths. For example, one could consider regulations that would specify the amount of reverse thrust, or the deceleration that an aircraft must follow on the runway; or prescribe a specific range for heights over threshold, touchdown point, and approach speed. One could consider instituting rules that specify the choice of exit for a landing operation. In other words, more of the landing parameters could be made the subject of rules and regulation and not left to the discretion of pilot and controller. The practical feasibilities of particular measures need further investigation. Such changes will no doubt complicate the approach and landing procedures, and will increase the control functions associated with an operation. Thus the impact on air traffic and ground control capacities would have to be assessed.

To supplement this development of rules and procedures, it may be necessary to make the verification of the abilities of aircraft and of pilots to follow these procedures a part of the certification process.

This again suggests that logistic, administrative and political issues will have to be dealt with, as they arise in the process.

Other procedural means

Pilot and airline motivation can be enhanced to a certain extent without resort to any of the rather extensive strategies mentioned in the previous paragraphs. The benefits are of course likely to be correspondingly less. Some of the less involved procedural aspects of pilot and airline motivation would include preferential runway assignments influenced by the relative location of exits and terminals, and integration of approach and ground controls in order to simplify the process of clearance from the runway to the gate position. Many of the other innovations addressed elsewhere in this study, having to do with information flow and with improved air traffic control technology, will help to motivate the users of the runway system to increase the efficiency of their use.

System requirements

There is little by way of technical system requirements that would be needed to implement this concept. One clearly identifiable requirement is related to the pricing concept. This is automated occupancy time measurement and accounting. This system would be needed in order to have an on-line capability for measuring the runway occupancy time for each operation, and for performing the necessary data management that would provide for efficient accounting. Given that controller and pilot workload are heavy during periods when runway occupancy time is important, and when a pricing system might be in effect, it is important that this system be automated and independent of controller and pilot functions.

In addition, it would be necessary to collect data on aircraft runway performance in order to establish a reasonable and efficient pricing system, and to identify the potential for further improvement. Aircraft runway performance monitoring could be part of the occupancy time measurement and accounting system, or it could be a separate system. If separate, it also would need to be automated and independent of controller and pilot functions.

Evaluation

Benefits. It is very difficult to make an accurate assessment of the benefits that can be achieved from pilot and airline motivation. A thorough study of airline costs and motivations, and analyses of pilot behavior and human factors would be essential for such a task. Nonetheless, one can use the evidence available to surmise the orders of magnitudes of potential savings that can be achieved. There have been some previous studies of the runway occupancy times for different airlines under essentially similar conditions. In one such study (Koenig: 1978) occupancy times for United and Trans World Airlines were compared for the same runway at Los Angeles airport. Due to the relative locations of the airlines' terminals and the exits on runways 25R and 25L, it was observed that United Airlines achieved occupancy times 5 to 15% lower than Trans World, and much of that was attributed to the fact that the former carrier could benefit from using the earlier exit due to terminal location. In another experiment at Denver Stapleton airport, pilots were consistently asked by controllers to expedite and exit as soon as possible. Savings in occupancy time of approximately 20 seconds were reported. (Schoen et al: 1979).

The TSC data analyzed in this study can ... d some light on the potential reductions in runway occupancy time that can be achieved by pilot and airline motivation. Data from operations on runway 27L at Atlanta with an aircraft fleet mix of predominantly DC9 and B727 aircraft show a standard deviation of occupancy time of 10% of the mean for groups of aircraft using the same exit.

This suggests that pilot and airline motivation could result in runway occupancy time reductions of the order of 10 seconds This would give an increase in runway capacity at a typical airport with a typical current fleet mix of about 6%. Preferential assignment of flights to runways could also achieve savings through reduced taxi time.

<u>Costs.</u> No significant capital facilities or operating costs are involved. System development costs are likely to be moderate for the occupancy time measurement, accounting and performance monitoring equipment. There may be some increase in aircraft operating costs on the runway as pilots attempt to reduce occupancy times, but this is more than offset by the delay reduction of the capacity increase. Implementation costs are likely to be moderate and primarily incurred in the development and approval of new procedures, and with pilot and airline familiarization.

<u>Impacts.</u> There may possibly be a small reduction in safety margins and passenger comfort due to less conservative aircraft handling on the runway. Pilot workload may be increased due to the reduced reaction time with shorter runway occupancies, and controller workload may increase due to changed ATC procedures and local/ground control coordination.

Other considerations. A moderate to long lead time may be required to develop and implement the new procedures. The measures are easily applied at existing airports and no changes are required to the aircraft fleet. Procedural differences between airports could be transparent to pilots. Failure of the automated time measurement and accounting equipment would not reduce runway capacity. Full benefits are achieved as soon as the new procedures are implemented at a given airport, and the benefits and costs occur only at those airports with the new procedures. The initial research and development costs are likely to be quite low, with a rapid build-up of benefits after implementation. Existing funding procedures appear to be adequate for the research and development program and implementation of procedural changes.

IMPROVED PILOT AND CONTROLLER INFORMATION FLOW

Objective.

There is evidence that aircraft are not fully utilizing their existing performance capability, such as the large standard deviations in runway occupancy time, even after controlling for differences in exogenous factors such as aircraft type and weight. This variation in actual performance of the system is due in part to uncertainty on the part of the pilot or the controller, arising from a lack of information. The result is a conservative approach to operating the aircraft or controlling traffic, in which pilots pass up exits they could have taken, separations on approach are unnecessarily increased, departures are not released when they could have been, and aircraft reduce speed on the runway too early or late. Improved precision in flying the final approach and deceleration on the runway will lead to reductions in the standard deviation of runway occupancy time.

Measures to improve the information flow may be directed at the pilot, the controller, or the flow of information between pilot and controller. The pilot requires information on aircraft position and speed and deviation from optimal position and speed, as well as information on ambient conditions and nearby traffic. The latter information is needed partly to help the pilot determine the optimal position and speed, and partly to permit the exercise of ultimate responsibility for the safety of the flight. This information should be accurate, timely and presented in as simple a manner as feasible. The controller requires information on the aircraft status, intentions and capabilities. This information should be provided in a manner that is compatible with the controller's other tasks and that minimizes the need for voice communication with the pilot.

Pilot information

Pilot information innovations could provide information that is not currently available to the pilot (or is not available in a readily usable form), could provide existing information in a more accurate or timely way, or could present information in a simpler or more convenient manner. Information innovations can be grouped according to pilot tasks as follows:

1. Maintain precision on final approach
   a) Head-up display
   b) Coupled autopilot to touchdown (cat IIIa approach)
   c) NAVSTAR/INS approach aid
   d) Improved VASI/approach lights
   e) Improved ILS/MLS.

2. Determine approach speed and deceleration profile
   a) Ground speed indicator
   b) Cockpit display of traffic information
   c) Ambient condition display (wind, runway surface condition)
   d) Improved exit location information.

3. Identify exit and maintain deceleration profile
   a) Aircraft runway guidance
   b) Improved exit marking and lighting
   c) Improved runway pavement marking.

4. Maintain safety margins during approach and landing
   a) Head-up display
   b) Cockpit display of traffic information
   c) Improved ambient condition information.

Support for the fourth task contributes indirectly to reducing runway occupancy time, since improvements in the ease or accuracy of maintaining safety margins may lead pilots to make fuller use of other means to reduce runway occupancy time, either by providing reassurance that safety is not thereby compromised or by reducing workload and thereby releasing time for other tasks.

Runway deceleration profile guidance

In general, an aircraft will not touch down and then maintain maximum deceleration until it reaches an exit at exit speed, although such a deceleration profile would give the lowest possible runway occupancy time. Such a profile of course requires that an exit be located precisely at the point where exit speed is reached, and that the pilot realizes that maximum deceleration must be maintained in order to utilize the exit. In practice it is very unlikely that an aircraft would follow such a profile, since even if the aircraft touched down at the optimum point, any reduction in deceleration by the pilot would cause the aircraft to overshoot the exit. In general, the deceleration profile can be characterized by a period of initial deceleration after touchdown to assure a safe roll-out, followed by a period during which the aircraft decelerates slowly on the runway toward the exit selected by the pilot, followed by a period of more rapid deceleration as the aircraft approaches the exit. The initial deceleration is usually performed with reverse thrust, while the final deceleration is usually performed with the wheel brakes. It appears fairly common practice to reduce the speed to about 60 knots with the reverse thrust, before reducing power and using wheel brakes.

For any given touchdown point and speed, the runway occupancy time will be a minimum if the aircraft rolls at high speed to the point at which maximum feasible deceleration will reduce the speed to exit speed just as the first achievable exit is reached. However, a pilot concerned about overshooting the exit will tend to initiate the final deceleration too early, and may maintain the initial deceleration after touchdown for longer than is necessary to secure the landing. Both actions will increase runway occupancy time above the minimum achievable. It is therefore desirable to provide the pilot with deceleration guidance that indicates when to terminate the initial deceleration and when to commence the final deceleration to the exit. It may also be desirable to indicate to the pilot which exit this deceleration profile will utilize. The target profile to be followed should take account of such factors as:

- Aircraft type and deceleration capability
- Aircraft weight
- Wind strength and direction
- Runway surface condition.

If the position and speed of the aircraft is known at touchdown, together with the above factors, the required profile can be computed.

The profile must be displayed to the pilot. A digital display of actual and target deceleration is cumbersome, and does not account for deviations of the aircraft from the target profile. A better method is to provide a real-time moving target location. If the aircraft decelerates too much, it will drop behind the target and the pilot can reduce the deceleration to catch up. If the aircraft does not decelerate enough, it will overtake the target and the pilot will have to increase the deceleration to let the target catch up with the aircraft. This suggests that the maximum target deceleration should be somewhat less than the maximum possible deceleration of the aircraft to allow for deviations from the target profile.

One way to display the target location to the pilot would be to utilize the runway centerline lights. If these lights were independently controlled, they could be turned either on or off in sequence to give the illusion of a moving light or gap in the lights. The pilot would then decelerate in order to try to keep the aircraft nose a short distance behind the target. Even if the aircraft overtakes the target, the pilot simply increases the deceleration until it appears again in front of the aircraft. The target exit could be indicated with flashing taxiway centerline or edge lights, or with a low power strobe light beside the exit.

The computation of the deceleration profile and the control of the runway lights can be performed on a real-time basis using standard micro-processor technology. The position and speed of the aircraft on the runway could be determined by using pairs of infrared light beams across the runway at wheel height at suitable intervals. As the beams are interrupted by the aircraft wheels, a signal can be sent to the micro-processor, which can compute the aircraft speed from the time delay between the signal from two adjacent beams. Alternatively it may prove possible to utilize an output from Airfield Surface Detection Equipment radar or other special purpose radar. One disadvantage of using a scanning radar is that speed must be computed from successive positions on consecutive scans, requiring a fairly high scan rate. Small errors in position from successive returns may lead to large errors in estimated speed. Wind speed and direction could be automatically input from sensors on the airfield. Runway surface condition could be input from a control panel in the tower. The aircraft type and weight could also be input from the tower. The micro-processor could be preprogrammed with the deceleration capability for each aircraft type. The tower could obtain the landing weight data from the aircraft by radio and this, together with the data entry, would increase both pilot and controller workload.

Several alternative approaches are available, including a special purpose transponder on each aircraft that replies to a low power interrogating unit with the aircraft type and weight as the aircraft crosses the threshold (this might require some data entry by the flight crew during approach), output from the Automated Radar Terminal System (ARTS) computer to give aircraft type, with aircraft weight inferred from approach speed, or data from airline operations.

In the event that it becomes apparent that the aircraft is going to overshoot the target exit or that the pilot is not following the deceleration profile, the micro-processor can provide a revised deceleration profile to the next exit. The micro-processor could also be programmed to monitor the deceleration performance of each aircraft type and update its data bank on deceleration capabilities.

Controller information

As with pilot information, controller information measures could provide information that is not currently or readily available to the controller, could provide existing information in a more precise or timely way, or could present information in a more convenient manner. The controller's problem is somewhat different from the pilot's, in that the pilot must monitor a very large amount of diverse information covering all aspects of the operation of the aircraft, while the controller is only concerned about a small subset of this. The controller, on the other hand, must coordinate this information for several aircraft at once. The controller requires information on both the current and expected future position of the aircraft, as well as the capabilities of the aircraft and the intended destination on the airport. Information measures may be grouped according to controller tasks, as

1. Maintain minimum safe separation between aircraft
   a) Digital threshold headway/separation display
   b) Aircraft airspeed limitations
   c) Automate departure release/go-around decisions.

2. Anticipate runway occupancy time
   a) Aircraft speed and touchdown point
   b) Aircraft acceleration/deceleration potential
   c) Pilot intentions.

3. Advise pilots of exit to use
   a) Aircraft deceleration potential.

The mechanism for providing this information to the controller deserves some consideration. In the case of the approach controller, the information can be displayed directly on the radar screen, along with the other ARTS alphanumeric data. In the case of the local controller, the information could be obtained from the BRITE display in tower cab.

Evaluation

The foregoing measures achieve a reduction in runway occupancy improving the precision of the final approach, by reducing the buffer required to allow for variation in the actual time between threshold and exit, or by operating closer to the optimum deceleration profile on the runway. Analysis was performed assuming a 50% reduction in the standard deviation of the height over threshold, and operation on an optimum deceleration pr[illegible]ile based on a maximum deceleration of 6 ft/sec^2 and an 80 knot roll-out.

Benefits. This analysis gave a reduction in runway occupancy time for a typical runway varying from 2 seconds for the improved approach precision to about 15 seconds for the optimum deceleration profile. It was assumed that the buffer between arrivals could be reduced by 5 seconds with improved controller information. These occupancy reductions give up to 7% corresponding increase in runway capacity under typical conditions.

Costs. Capital requirements for the necessary aircraft instrumentation and ground aids are likely to be moderate. Operating costs of the new equipment and landing aids are also likely to be moderate. Development of the new instrumentation and aids will require a significant research, engineering and development program for a few years. The implementation costs would be largely those associated with familiarizing pilots and controllers with the new procedures.

Impacts. It is likely that a moderate improvement in safety would result from the better information. The impact on pilot workload is not clear, with some additional tasks and some simplification, depending on the details of the innovations implemented. The net change is not likely to be great. It should be possible to design the innovations so that there would be no significant change.

Other considerations. Development of the new equipment and landing aids would require a moderate lead time for implementation. No compatibility problems are anticipated with the existing aircraft fleet. The innovations can be easily introduced at existing airports, and ground-based equipment can be provided selectively at busy airports. The benefits from improved aircraft instrumentation occur only at the busy airports while the costs are spread over all use of the aircraft, and these benefits increase incrementally with the introduction of the instrumentation into the fleet, giving low initial benefits and slow buildup. The full benefits from ground aid improvements occur at a given airport as soon as the facilities are operational.

RUNWAY EXIT AND ENTRANCE DESIGN

Objective

In its most simplified form, the landing process may be characterized as a phase of deceleration in the air from approach speed to touchdown speed, followed by touchdown and deceleration to exit speed, then taxiing on the runway to the first available exit. In actual practice, the pilots frequently anticipate the exit location somewhat and decelerate rapidly to a speed higher than exit speed, taxi to their chosen exit at a reduced deceleration rate, then increase the deceleration to reach exit speed as they approach the exit. This reduces runway occupancy time, but still involves a period during which the aircraft is essentially taxiing rather than decelerating, and hence occupying the runway while not in fact using it for the purpose of making the transition from flight to taxi speed.

In the take-off situation, the aircraft taxis onto the runway, often from a stationary position holding clear of the runway, executes a sharp radius turn to line up with the runway, then power is applied and the take-off roll commences. Frequently the engines are run up to full power before the brakes are released, either because of runway length constraints or for the crew to check the engine performance. During the maneuver into position and engine run up, the runway is occupied without being used for the purpose of accelerating the aircraft to flying speed.

The above processes suggest three potential ways to reduce runway occupancy time:

- Position exits to permit continuous deceleration to exit speed, eliminating the time involved in taxiing on the runway.
- Design exits to permit higher exit speeds, reducing the time spent decelerating on the runway.
- Design runway entrances to permit initial acceleration to take place off the runway and before runway occupancy commences.

The ideal exit configuration would provide a continuous exit over the full length of the runway (or at least over the central portion), designed so that aircraft can negotiate the exit at high speed with maximum choice of exit path. Today, exits are located at discrete intervals and exit design speeds are limited by cost and other considerations. The objective of the improvements described in this section is to attain some of the benefits of the continuous high-speed exit, while still using discrete exits.

Exit design and location

The subject of the design and location of exit taxiways has received considerable attention over the years. Various methods have been developed to determine the appropriate location, and standard designs have evolved. Much of the existing planning and design criteria rely for their validity, however, on observations conducted in the past on a somewhat different aircraft fleet. As the aircraft fleet evolves, the characteristics of the new aircraft may require changes in the existing standards.

The following three changes represent areas where a revision of the present standards may achieve reduced runway occupancy times:

- Revised criteria for the location of exit taxiways in the light of aircraft fleet characteristics and exit design.
- Establishment of adequate clearance criteria between the runway and the circulation taxiway system to permit an aircraft exiting at high speed to safely come to a stop before reaching the circulation taxiways.
- Changes in the design of exits, fillets and taxiway geometry and grading to encourage higher exit speeds and the matching of exit radius to the aircraft types using those exits, together with associated improvements in exit marking and lighting.

Runway entrance design

The use of high-speed runway entrances has already been initiated in the existing environment by some airlines which use the high-speed exits in the reverse direction at certain airports. However, these exits have not been designed for entrance traffic nor have they been located in the optimum position from the standpoint of reducing departure runway occupancy time. Therefore, new criteria are required to guide airport planners in providing such high-speed entrances.

Evaluation

The foregoing improvements represent complementary ways of achieving direct reductions in runway occupancy time. Analysis of a typical runway configuration and aircraft performance was undertaken to determine the effect of relocating exits to the optimum point for a 40 knot exit speed, the use of 60 knot and 80 knot exit speeds, and the use of a continuous exit with an 80 knot exit speed.

Benefits. Relocating exits appears to give runway occupancy reductions of up to 9 seconds. Use of increased exit speeds could reduce runway occupancy by 17 to 24 seconds, while the use of a continuous exit could result in up to 30 seconds reduction. These reductions in runway occupancy give a corresponding increase in runway capacity of up to 8% at a typical airport with typical aircraft mix. There may be some additional benefit from the reduction in aircraft operating costs through reduced braking and power use.

Costs. Capital requirements consist of new construction at major airports, and are likely to be quite moderate. Operating costs are low, consisting only of the incremental maintenance. Research and development will be required to develop and validate the new design criteria. The costs of implementation will be low, involving the promulgation of advisory materials.

Impacts. There may be a small improvement in safety as a result of more efficient runway operations, and a possible slight improvement in passenger comfort as a result of better aircraft handling on the runway.

Other considerations. Moderate lead time would be required to develop new criteria, with relatively small R&D costs. Funding procedures for major airport development are already well established, while major costs need only be incurred at those airports where significant benefits occur. There appear to be no compatibility problems with the existing aircraft fleet, although potential difficulties may arise in applying criteria at some existing airports. The full benefits occur at a particular airport as soon as the new criteria are implemented.

HIGH DENSITY AIRFIELD OPERATION

The airfield contains pavement for runways, taxiways, and aircraft parking; and spaces between the pavement. Most of the pavement is occupied for relatively short intervals which are generally followed by longer intervals of disuse. The spaces between the pavement are generally unused, except in emergency. The relatively low utilization of the airfield is due to airfield design and operating standards which reflect accumulated experience and safety concerns.

The objective of this package of innovations is to obtain airfield capacity increases (a) by obtaining increased use of the existing airfield pavement, and (b) providing additional pavement in part of the empty space on the airfield. Certain Engineering and Development Program products are required to obtain the greatest capacity increases.

This package of innovations deals with the issue of runway occupancy time by making available additional time "slots" on the airfield for aircraft to land and take off. The slots are dedicated times for sections of airfield pavement, and are provided either by better utilizing existing pavement or on new pavement. This package of innovations does not depend on changes in aircraft performance or other means of reducing runway occupancy time, but can provide additional benefits if such reductions are available.

Increased Use of Existing Pavement

Gains in airfield capacity can be obtained from increased use of taxiways and runways.

At most large airports, taxiways are constructed parallel to the runways to facilitate aircraft flow. In many cases, these taxiways can be used as runways for certain classes of aircraft, normally small aircraft of 12,500 lbs or less. Removal of these small aircraft from the runways permits increased use of the runways by large aircraft. For example, a small aircraft will normally take some 20 or 30 seconds of runway occupancy time. Diversion of this aircraft to a taxiway opens up a runway slot for use by large aircraft arrivals or departures.

Several factors may constrain use of taxiways as runways. For example, the lateral separation between the taxiway and runway may not meet current minimum requirements for independent operation. In this situation, dependent operations can be used with advantage.

In addition, the navigation and air traffic control systems may not have sufficient resolution to permit full use of the taxiway as a runway in instrument meteorological conditions (IMC). Pending gains in resolution that may result from the FAA Engineering and Development Program, two means of use of the taxiway are available. First, small aircraft that can fly below cloud cover (for example in weather with 900 feet ceiling and 3 miles visibility) could conduct an approach by visual reference. Secondly, the runway can still be used to alternate arrivals and departures that are synchronized with main runway operations.

Use of taxiways as runways is currently restricted to daytime operation, and is often further restricted by requirements to use the taxiway for aircraft circulation between the runways and the aircraft parking area. Each of these constraints can be alleviated by implementation of Dynamic Airfield Sectorization and Lighting (DASL). The taxiway would be fitted with appropriate taxiway, runway, and approach lights that can be controlled dynamically in the control tower. The lighting could be used both in night-time and day-time to give clear guidance to traffic that the pavement is currently functioning as a runway or as a taxiway.

The DASL concept can also be used to assist large aircraft to leave the runway at higher speeds. High speed exits at many major airports are not used at design speed because there is insufficient distance available for the aircraft to decelerate on the exit to taxiing speed and stop if necessary before contacting ground control and entering the taxiway system. Designation of part of the taxiway system as a portion of the runway under the jurisdiction of local (tower) control would provide the deceleration areas needed to allow aircraft to exit at design speed. DASL would provide the clear guidance needed to aircraft and controllers that the area was reserved for exiting aircraft. When not required for an exiting aircraft, the designated area could be returned to ground control and the lighting system switched to taxiway lighting.

Use of displaced thresholds for arrivals and intersection take-offs or displaced departure points for departures also offer the potential for capacity gains. A displaced threshold requires aircraft to remain airborne over the runway until the threshold is crossed. The threshold could be located to minimize arrival runway occupancy time by providing the optimal distance between the threshold and existing exits. In addition, the arrival also travels more quickly to a distance down the runway that would permit departures to enter the runway and commence take-off roll from the departure end of the runway. (This concept would require a rule change for large aircraft.)

Intersection take-offs provide similar opportunities for capacity gains. With an intersection take-off, a following arrival can cross the landing threshold at an earlier time than would be possible for a departure from the runway end. (The 2-mile IFR departure/arrival rule and the "6000 feet and airborne" departure runway occupancy rule are satisfied more readily). While not a necessary condition for satisfactory operation of displaced thresholds and intersection take-offs, use of a DASL system to dynamically adjust take-off and landing points could provide additional benefits.

In IMC, full advantage is not taken of all runways at most airports. If the separation between parallel runways is less than specified standards, then the two runways cannot be used independently. In addition, independent instrument approaches to converging runways are not currently permitted because of concerns about simultaneous missed approaches. These constraints on the use of the terminal area airspace put extra pressures on the runways that are available for use. Products of the FAA Engineering and Development Program have the potential for alleviating these constraints and obtaining fuller utilization of the existing runways. For example, the additional accuracy and reliability of the Microwave Landing System (MLS) offer the potential for reducing the required separation between parallel runways for certain classes of aircraft and for providing precision departure guidance for simultaneous missed approaches.

Addition of New Pavement

Gains in airfield capacity can also be obtained from provision of additional pavement for runways and taxiways. This additional pavement can be used in accordance with the concepts described above for existing pavement.

Many airports have available space for the development of additional runways. Environmental pressures from surrounding communities (and the difficult institutional process for approval of runway construction) have restricted airfield development at these airports. Close parallel and short runways present opportunities for development of new runways with the least environmental, land use, and economic impact.

Additional exits and entrances for existing runways offer another means for reducing runway occupancy time. Locations and geometric layout should be tailored to site specifics to obtain the maximum benefit. Continuous exits and other exit layouts are discussed further in the Section on Runway Exit and Entrance Design.

As noted in the discussion above concerning aircraft deceleration on the exit taxiway, reductions in runway occupancy time can be obtained by using higher exit speeds and permitting deceleration off the runway. Even with designation of some taxiways to local control, the existing exit and taxiway geometry may not be adequate for higher exit speeds. New taxiway fillets, extra lengths of taxiway, and exit geometry modifications could permit the required higher speeds.

Use of some parallel taxiways as runways may increase the potential for congestion on the taxiway system. Additional circulation taxiways may facilitate the use of existing taxiways as runways by providing efficient connections between runways and taxiways that avoid the new taxiway-runway.

Evaluation

High density airfield operation provides the potential for higher airfield capacity both by allowing aircraft to exit from runways in less time and by providing more slots for landings and takeoffs on additional runways.

Benefits. Improvements in exit geometry and utilization could reduce runway occupancy time by 20 to 30 seconds, thereby increasing IFR airfield capacity by up to 25 percent with today's ATC system. Additional runways could double airfield capacity if located and operated effectively.

Costs. Capital costs for new pavement, airfield lighting equipment, and new navigation and landing aids are likely to be substantial and require a major research and development program. Operating costs are moderate and consist primarily of facility and equipment maintenance. Implementation costs will include pilot and controller training and familiarization with the new procedures.

Impacts. Although the existing facilities are subject to more intense use than before with these innovations, they have been conceived so that there is no significant change in the level of safety, or in controller or pilot workload. The increased activity may lead to a potential adverse noise impact on the airport environs.

Other considerations. The increase in the utilization of the airfield may lead to possible problems with taxiway congestion. Additional airspace may be needed around the airport. There may be potential local community opposition to additional pavement due to concerns over aircraft noise and the consequences of airport growth.

INTEGRATED LANDING MANAGEMENT

Objective

The underlying concept behind this package of innovations is that the operation of the final approach and runway should be considered in concert, and should be viewed in a four dimensional perspective. Aircraft on approach for a landing may be separated by a distance separation; but more importantly, they should follow a prescribed path in time and space so as to maintain a specific headway over the threshold. This headway would be matched by the time required for runway occupancy, whether for the preceding landing, or that landing plus an intermediate take-off. This headway is to be achieved provided that certain safety requirements are met along the final approach path. These requirements are currently expressed as separation (distance) but might just as well be specified in headway (time interval) terms. There appears no reason to believe that adequate safety cannot be achieved through time separation with as much confidence as through distance separation.

<u>Time versus distance separation</u>

It is essential for the operational modifications that would be necessary to implement a four dimensional system in which headways and runway occupancy times can be matched, that aircraft separation on a time basis be accepted. To support this, a thorough analysis of the safety implications and perceptions should be conducted. An operational investigation should also be made to determine what are the necessary procedural steps to achieve this change, assuming that the needed technical innovations are available.

Consider two cases, in the first of which aircraft are on a common approach path separated by 3 nautical miles and flying at 180 knots, and in the second of which aircraft are separated by 2 nautical miles but flying at 120 knots. In both cases, the headway between aircraft is 60 seconds. Assuming a distance variability according to a normal distribution with zero mean and 1 nautical mile standard deviation for both cases, the collision risk at different distances along a 9 nautical mile common approach path can be calculated. Assuming no action by pilots or controllers to correct the separation along the 9 mile common path, it can be shown that the instantaneous collision risk at a given point is not substantially different in either case. The 3 nautical mile separation is not necessarily safer than the 2 nautical mile separation if aircraft are flying at the higher speed.

Another aspect of headway separation is the wake vortex problem. In the absence of wind, it can be said that the vortex will not move horizontally in any particular direction but will dissipate gradually in place. If this is the case, then it would again follow that a time separation is appropriate for mitigating the risk of vortex turbulence problems, since it is time that is needed for the vortex to dissipate and not distance. Further investigation of the times required for vortex effect dissipation would be a necessary requirement for the implementation of headway separation procedures.

Integrated Landing Management

The concept of Integrated Landing Management emerges as a major procedural change in the way runway systems are operated. The implications of this concept go beyond runway occupancy time, but what is of direct concern to this study is that Integrated Landing Management may in fact be a prerequisite for realizing the full gains from reductions in runway occupancy times. The implementation of Integrated Landing Management (ILM) is essentially a procedural innovation, but it requires a number of technical innovations. Some of these innovations have been identified elsewhere in this study.

The basic requirement is that for any given runway, and for a given set of environmental conditions prevailing at any moment, an automated system is used to calculate the anticipated runway occupancy time for landing aircraft. This calculation will be based on the available exit locations and designs, and on the capabilities of the aircraft. On the basis of calculated runway occupancy times, the appropriate headway and approach speed between landing aircraft can be determined. The stream of landing aircraft is then controlled in such a way as to achieve these operating conditions as closely as possible. The intent of ILM is to:

- Determine the minimum runway occupancy time possible under a given set of conditions.

- Determine the appropriate headways consistent with the runway occupancy time in order to maximize the utilization of the runway.

- Exercise the control necessary to achieve the operating parameters thus determined. This control can be exercised provided that pre-specified safety separation standards are not violated. These standards could be in the form of distance or time, and would include the necessary buffers usually provided in order to allow for random fluctuations.

In order to develop the capabilities of ILM, the following system requirements are identified:

Automated Headway Display (AHD): The main premise of the concept of Integrated Landing Management is that flight safety rules might be specified in headway terms. Maintaining a planned headway between aircraft at the threshold follows from the attempt to match these headways with the required runway occupancy times in order to optimize the utilization of the runway. The capability to automatically display the headway between pairs of aircraft both on airborne instrumentation and in the air traffic control positions would greatly enhance the ability of pilots and controllers to maintain planned headways. It would significantly increase controller workload to implement traffic control rules on the basis of headways without a headway display technology.

The basic version of AHD would consist of a display of the headway between every aircraft on the final approach and the preceding aircraft. After the preceding aircraft crosses the threshold, the display would show the time to the threshold. Additional information could be built into an upgraded AHD in which both the actual, and an ILM-generated target headway are both displayed. This may further reduce pilot and controller workload in implementing Integrated Landing Management. Speed control can be exercised considerably more easily with the upgraded AHD.

Real-time Aircraft Profile Generator (RAPG): This system would develop the capability for online computation of the path to be followed by each aircraft in the stream. The general scheme for doing this could follow a procedure such as shown in Figure 4.5. Starting with a given runway and its set of exits, the appropriate exit speed is determined. For a given aircraft in the stream a calculation will then be performed to determine simultaneously the approach speed and the deceleration profile that would result in the minimum service time including runway occupancy and headway. If this profile is feasible, then the aircraft trajectory is defined and its location (in time and space) within the approach stream is decided. If it is not feasible, then the next exit is selected, and the process repeated. This procedure will be done automatically for all aircraft in advance of their entry into the final approach, so as to minimize the need to change aircraft trajectories after that point.

The possibilities for optimization with this system can be significant and the potential gains in capacity, and reductions in runway occupancy time, justify the necessary further research.

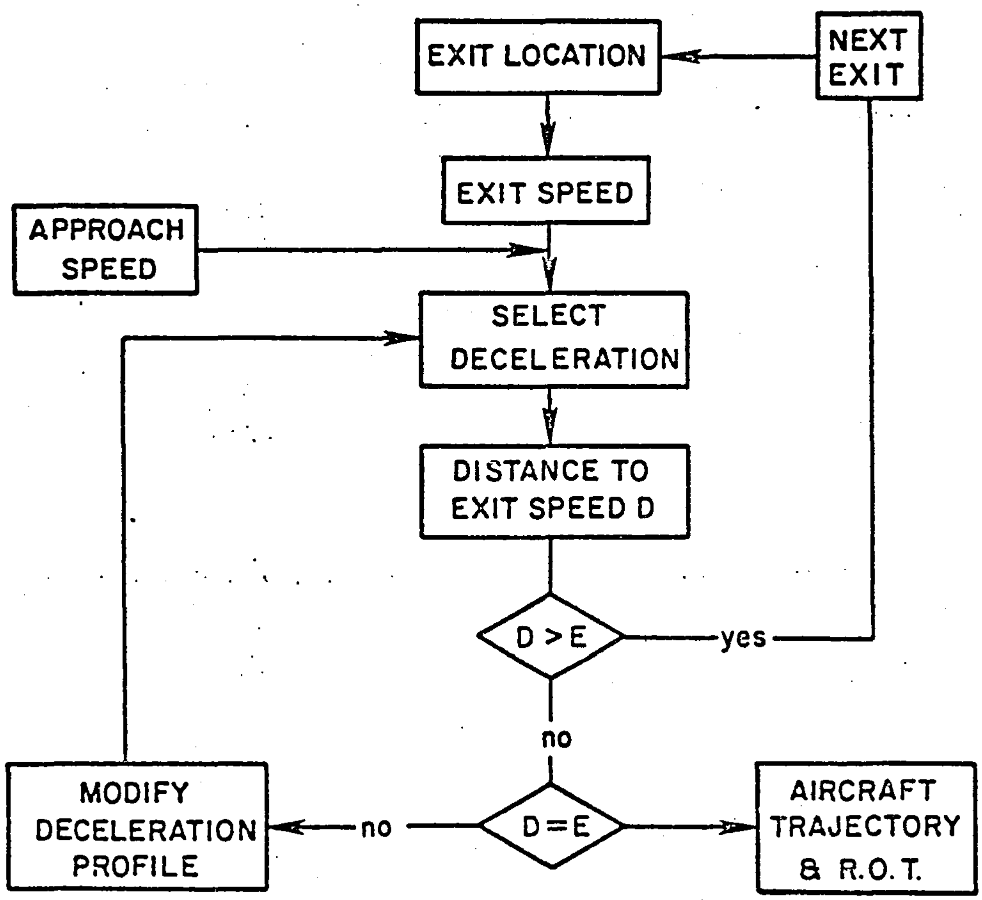


FIG. 4.9 Real-time Aircraft Profile Generation Logic.

Evaluation. In order to obtain a preliminary assessment of the potential benefits that can be achieved with Integrated Landing Management, two cases are investigated. In the first case, the determination of appropriate headways between landing aircraft in order to match runway occupancy times implies that separations of less than 3nm may occur in some cases. In the second case, no separations are less than 3nm.

Case 1: In this case we postulate a stream of landing aircraft that have a minimum approach air speed of 125 knots, and an exit speed of 40 knots. This stream could be of DC-9 or B-737 type aircraft. The relationship between approach speed and runway occupancy time to 40 knot exit speed is given by Figure 4.16, based on a simple computer simulation. In order to assess the potential benefits from ILM we postulate a baseline operating situation where the aircraft are approaching at 130 knots, separated by 3 nautical miles. We postulate no wind so that airspeed and ground speed may be used interchangeably. In a landings-only situation, the headway between the aircraft will be 83 seconds and the hourly capacity of a runway would be 43 landings. If we were to compute the appropriate headways between aircraft in such a way as to match runway occupancy times, as was demonstrated in Figures 2.5 and 2.6, and as would be done under ILM, then the results given in Table 4.2 would be obtained.

In Table 4.2 the headway is chosen to match the runway occupancy time at the approach speed indicated. This runway occupancy time consists of the time from the threshold to the exit speed of 40 knots plus 10 seconds for exit maneuvering. It can be seen from the table that it would be desirable in this case to increase approach speeds, as much as

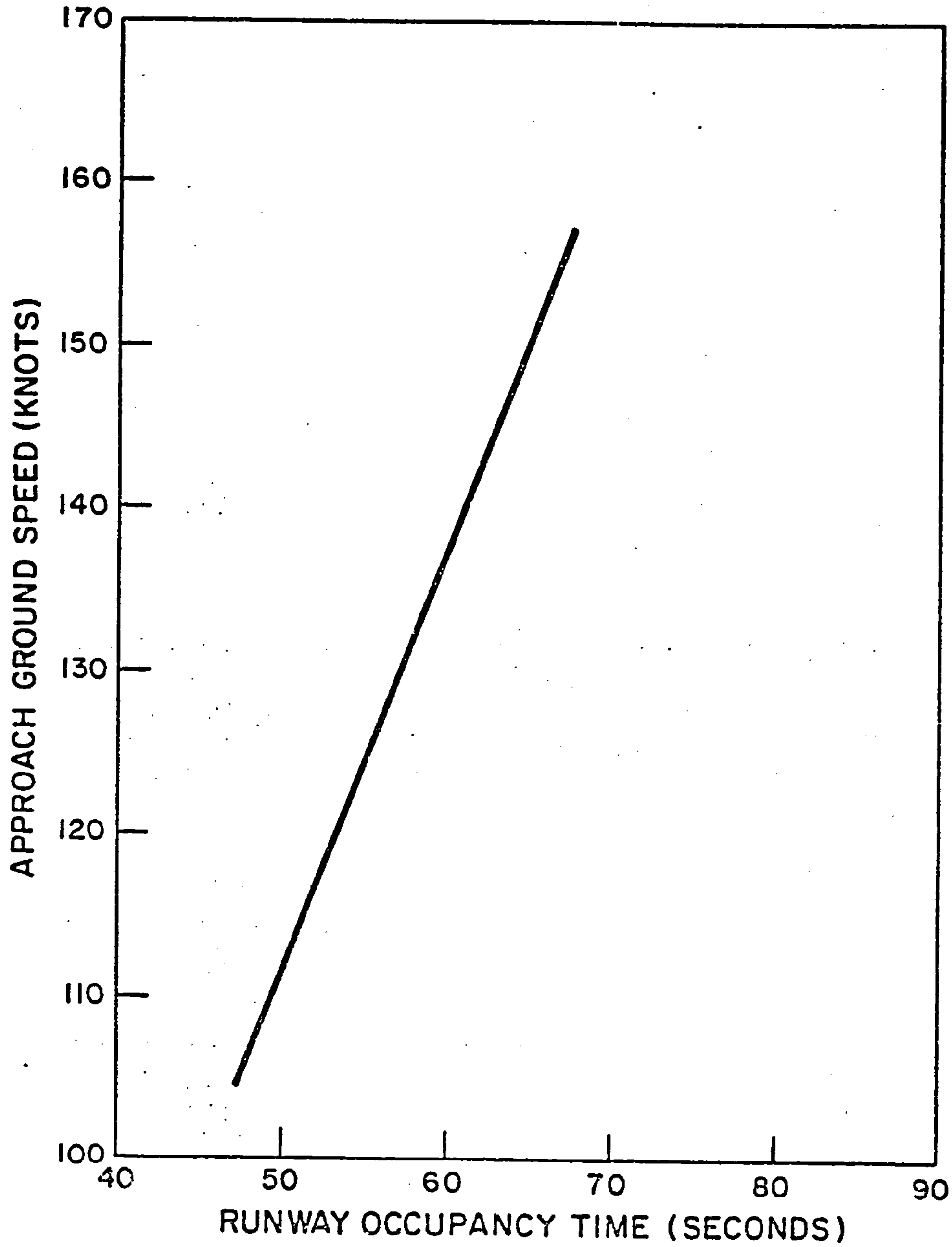


FIG. 4.10 Effect of Approach Groundspeed on Runway Occupancy Time under Typical Conditions.

Table 4.2

Effect of Approach Separation on Runway Capacity with ILM Landings Only

Separation (nm)	Approach Speed (knots)	Headway (sec)	Capacity (a/c per hour)
3	163	67	54
2.5	146	61	59
2	132	53	68

Table 4.3

Effect of Approach Separation on Runway Capacity with ILM Mixed Operations

Separation (nm)	Approach Speed (knots)	Occupancy Time (sec)	Headway (sec)	Capacity (a/c per hour)
4	137	56	106	68
3.5	124	51	101	71
3	112	46	96	75

practicable, in order to achieve higher capacities. The capacity gains will be of the order of 26% at 3 nautical mile separation; 37% with a 2.5 nautical mile separation, and 58% with a 2 nautical mile separation. These benefits can only be gained if the indicated approach speeds were feasible. While it is unlikely that 163 knots is a practical operating speed over the threshold, the inference is that any increase in speed is likely to result in benefits. These benefits are achievable with ILM without any of the innovations that could reduce runway occupancy time for any given approach speed.

<u>Case 2</u>: In the second case we maintain the same aircraft mix, but we postulate a mixed operation with a departure interleafed between every pair of arrivals. The baseline for this case is assumed to be a landing stream with an approach speed of 125 knots, and a separation of 4 nautical miles. This gives a headway of 115 seconds between landings, and a mixed operations capacity of 63 operations per hour. Under ILM we can postulate reduced separations and seek to match the headways between landing aircraft with the runway occupancy times of a landing and take-off. The runway occupancy time for a take-off is assumed fixed at 50 seconds and the landing occupancy time is computed as in the previous case: time to 40 knots plus an additional 10 seconds for maneuvering. The resulting headways and capacities obtainable with ILM are given in Table 4.3. We can see that ILM will not necessarily result in an increase in approach speed. Indeed, a capacity increase of 19% can be achieved by reducing approach speeds to 112 knots, and maintaining a landing separation of 3 nautical miles for mixed operations. Smaller reduction in separation (to 3.5 n.m.) together with essentially no change in speed (124 knots) will yield a 13% increase in capacity. An

increase in speed with the baseline separation of 4 nautical miles will yield a capacity increase of 8%.

These two cases demonstrate that considerable capacity improvement benefits can be achieved by implementing an ILM system. The exact magnitudes of these benefits cannot be determined without detailed analysis. However, it is likely that at least 10% increases in capacity are possible without drastic changes in procedures, and that with full implementation of an ILM program, the benefits could be much greater.

This analysis shows that the advantages of ILM do not necessarily stem from a reduction in runway occupancy time. Indeed, in a situation where the approach speed is increased, occupancy time is also increased. The important thing is the matching of occupancy times and approach headways. The potential benefits from runway occupancy time reductions can then be fully achieved.

Costs. Capital costs for acquisition of the necessary associated computer equipment will be moderate and operating costs limited to maintenance of the equipment. A substantial research, engineering and development program will be required to develop the details of the system. Implementation involves significant changes to ATC rules and procedures, with the associated costs of consultation, testing, approval, familiarization and training.

Impacts. There is no evidence to suggest any adverse safety impacts from the procedural changes. There is the possibility of some increase in pilot and controller workload as the requirements of the system become more clearly defined.

Other considerations. A major procedural change such as ILM may require a long lead time for implementation. There are no compatibility problems with the existing aircraft fleet since all the equipment is ground-based. The procedural changes could be made relatively "transparent" to the pilots, so they would not need to know whether ILM was in force at a particular airport. The costs need only be incurred at those airports where the benefits would justify implementation, and the full benefits would be obtained immediately upon implementation.

PROMISING INNOVATIONS

Although the six packages identified in the previous section all appear to give significant benefits in reducing the constraint of runway occupancy on capacity, they clearly involve very different levels of cost and other impacts as well as raising very different implementation questions. The development of the necessary equipment and procedures would also require different amounts of lead time. Thus, some of the innovations may be considered to be long-term measures, while others offer the opportunity to obtain runway occupancy improvements in the shorter term.

Short-term measures.

Short-term measures are considered to be those that could be implemented within the existing airfield geometry and with the existing aircraft fleet, without requiring major changes to existing procedures either for air traffic control or aircraft operation. For reasonably rapid deployment of new technology associated with these measures, the capital costs involved should preferably be able to be met by existing programs, such as the Airport Development Aid Program or the FAA's Engineering and Development Program. A number of innovations within the packages appear to offer significant benefits in relation to the resources required for their implementation.

Improved pilot and controller information. Several equipment developments could offer substantial assistance to pilots and controllers, particularly

- Aircraft deceleration profile guidance (ADPG)
- Automated headway display system (AHDS)
- Aircraft runway performance prediction (RPP)
- Automated departure release and go-around advisory system (AUTOGOAD).

The ADPG consists of micro-processor and airfield lighting switching technology which could be developed relatively quickly, and implemented on a progressive basis at critical airports. It is not even necessary that pilots understand the system (although it is almost self-educating) since if they ignore it, the resulting runway performance is no worse than before. The automatic data links between the aircraft and the system (using transponders, DABS, etc.) could be implemented as a later refinement, as airlines or the FAA feel it justified, to reduce pilot or controller workload. It would not matter if only some of the fleet were equipped with the special transponders, since those aircraft would gain the benefit of the reduced workload, and the other aircraft would be unaffected.

The AHDS and RPP are software developments that could be incorporated into the ARTS software, with control tower display monitors to assist the local controllers. The automated departure release and go-around advisory system could be based on a dedicated micro-processor with readout in the tower cab, receiving real-time input from the ARTS computer and ASDE radar.

Runway exit and entrance design. The modification of runway exit and entrance taxiways represents a class of measures that could be implemented on a highly airport-specific basis, where the existing airfield geometry permits and where justified by the expected benefits. The necessary construction costs should be well within the capital works budget of a major airport authority and are likely to be eligible under Federal airport aid programs. However, airport planners will require design guidance beyond that currently provided by the FAA Advisory Circulars and existing airport planning literature. This guidance should address

- Exit taxiway location
- High-speed exit and taxiway geometry
- High-speed runway entrance taxiways.

Exit taxiway location criteria contained in the existing FAA Advisory Circulars do not reflect the varying performance and operational characteristics of the particular aircraft fleet using a specific airport. Further research is required to better specify these criteria in situation-specific terms and to develop the appropriate design aids.

There is ample evidence that the present air carrier fleet are not using the existing high-speed exits in the manner intended in their design, while experience in Japan with a substantially modified design indicates that high-speed exits will be used if properly designed and located. There have also been recent empirical tests in the United States of alternative exit geometry. The results of these tests and this experience needs to be consolidated in the form of specific design criteria and appropriate design aids.

There are currently no design criteria for high-speed runway entrance taxiways. A program of research is required to develop the necessary design guidance to permit airport planners to determine where such entrance taxiways might be beneficial and how to design them.

Although all three measures noted above require further research before they can be implemented, this does not necessarily imply a long lead time before the first implementation. Not all airports will be in a position to commence construction at once, or find it necessary to. Preliminary research to establish tentative criteria for the first projects could be completed in under a year. The important point is that the research be ongoing, and include adequate funds to monitor the performance of the new projects so that the design criteria can be refined and improved with experience.

Pilot and airline motivation. The present system of pricing the use of the scarce runway resource in times of congestion provides little incentive for pilots to strive to reduce runway occupancy, or for airlines to establish procedures to encourage their pilots to do so. The local control request "Exit at first opportunity, company traffic on short finals" is known to encourage an early exit--the pilot is well aware of the cost to the airline of a missed approach. The formalization of these economic incentives could lead to a much more efficient utilization of the runway capacity.

Since during periods of heavy traffic, available runway time is the scarce resource, objectives of economic efficiency and maximum utilization will both be served by charging airlines for the time they occupy the runway. Such economic incentives will encourage airlines to develop operating procedures for early exit and prompt departure. Airlines operating smaller aircraft can take advantage of the shorter take-off and landing distances by making intersection take-offs and moving the touch-down point closer to the exit. These airlines will be encouraged to press for special-purpose runways and perhaps differential approach paths and threshold positions.

It is to be anticipated that many airlines may oppose such a radical change in pricing airport services, out of conservatism or because they receive a hidden subsidy by the present system. However, improved runway utilization ultimately benefits all users of the runway system by reducing delay costs, or permitting additional operations that would be denied by an arbitrary allocation of runway "slots". It is therefore necessary to perform a more detailed assessment of the benefits to be derived from such a pricing system in comparison to the hidden costs of the present system, so that implementation discussions with airlines and pilot groups can proceed on the basis of an evaluation of the facts as they appear to the various parties.

<u>Longer-term measures</u>

In the longer term, major improvements could be implemented in the aircraft fleet, in the procedures used to manage the flow of traffic through the final approach airspace and onto the runway, and in the airport configuration. These improvements have much longer lead times than those discussed in the previous section because they require substantial development of new technology, major changes in operating procedures that would require the agreement of different sectors of the industry and the retraining of pilots and controllers, or gradual replacement of the current generation of aircraft due to normal fleet turnover. However, the correspondingly greater potential benefits justify a closer examination of these options and the initiation of the necessary long-term research and development where the initial promise is borne out by a more detailed assessment.

Improved short-haul aircraft technology. The development of improved technology targeted at the growing market for specialized short-haul aircraft could significantly improve their runway occupancy characteristics. This would not only reduce the impact of increasing numbers of small aircraft on the conventional aircraft using the runway, but would increase their ability to utilize special-purpose runways, such as modified taxiways and portions of intersecting runways. Among the various improvements that could be considered, the most promising in terms of the anticipated benefits and the likely implementation requirements appear to be

- Enhanced deceleration and acceleration
- Enhanced exit turn capability.

Enhanced deceleration can be achieved through improved braking, an increase in the available reverse thrust, and an increase in deployable aerodynamic drag. Improved acceleration could be achieved through a higher thrust-to-weight ratio (which would also improve the available reverse thrust), or the acceleration time could be reduced by increasing the lift coefficient to reduce the lift-off speed.

Enhanced exit turn capability would require improved steering and landing gear (which might also be required to permit improved braking), while control stability problems could be addressed with active integration of aerodynamic, steering, and power controls.

Integrated landing management. Maximum runway capacity under any prevailing set of aircraft performance characteristics will be achieved when the aircraft speed and spacing on final approach are balanced so that the headway across the threshold is equal to the runway occupancy of the preceding arrival and any intervening departures. Achieving this balance will require a major change in approach control procedures and the development of the necessary display and monitoring equipment so that the controllers have the necessary information to advise pilots of the speed to maintain on final approach. While such a control strategy can be applied on a first-come first-served basis, further capacity gains might be achievable with optimization of aircraft sequencing.

Further research is needed to develop the analytical tools to assess how the benefits vary with the aircraft mix and prevailing conditions and to establish the specifications for the necessary control equipment.

High density airfield operation. Various measures are possible to increase the utilization of existing airport geometry. These measures include better control equipment to achieve multiple use of existing or new pavement and the addition of new pavement in parts of the airfield not currently being fully utilized. Among the more promising measures are

- Use of taxiways as runways
- Dynamic airfield sectorization
- Construction of close parallel or short runways.

Use of conventional air carrier taxiways as runways for smaller aircraft has already been implemented at some airports, as has the use of part of conventional intersecting runways for intersection take-offs or stop-short operations. Further research is needed to identify other potential applications of these ideas, and to establish evaluation criteria to assess particular proposals.

An increase in the number of operations within a given area will put heavier demands on the air traffic control system, and consideration should be given to better ways to assess the safety implications of a changed operating environment and to the development of better control tools. Dynamic airfield sectorization, using airfield lighting that can change color in order to clearly mark the current function of a particular stretch of pavement, could permit a real-time modification of the airfield geometry to respond to changing traffic needs.

Combinations of innovations

Thus far the innovation packages have been analyzed as coherent, yet independent, strategies to reduce the constraint of runway occupancy on capacity. Just as the individual innovations were combined into packages, so the innovations in separate packages could be combined into a coherent program.

Several of the packages have strong interactions. Changing the operating characteristics of short-haul aircraft will change the requirement for runway exit design or alter the benefits and impacts of high density airfield operation. However, it should also be realized that while some measures are mutually supportive and may enhance the benefits to be derived from each, such as improved pilot and controller information and integrated landing management, in general as runway occupancy is reduced, the costs of further reduction will increase. Therefore the implementation process should be viewed as a program, in which measures are combined as appropriate to achieve desired improvements.

This in turn implies that any further research should be pursued in the context of such a program, after particular innovations have been selected for further development. This selection process might require more detailed analysis than has been possible within the constraints of this study.

5. CONCLUSION

The previous chapters have identified a large number of individual innovations that, separately or in combination, can contribute to an increase in runway capacity by modifying aircraft runway occupancy characteristics. These innovations have been subjected to a preliminary evaluation and then grouped into a set of coherent packages for further analysis. This chapter documents the findings that result from that analysis and identifies the additional research that must be performed in order to explore the feasibility of implementing particular measures.

STUDY FINDINGS

Although this study has concentrated on measures to change aircraft runway occupancy characteristics, it has done so in the context of the wider issue of measures to increase runway capacity. In the course of the research it became clear that there are at least four different strategies to increase runway capacity, and that they interact:

1. Improve the air traffic control system to give closer spacing on the approach path, and hence shorter headways over the threshold, without changing aircraft operating characteristics.

2. Implement measures to reduce or eliminate speed or spacing differentials on approach, by using, for example, multiple approach paths with microwave landing systems (MLS) or wake vortex alleviation or avoidance.

3. Reduce runway occupancy times, either directly or by

permitting multiple occupancy.

4. Providing additional runways within the existing airfield configuration and increasing the number of approach streams.

The fourth strategy is closely related to the third, in that such measures as close parallel runways, use of taxiways as runways for small aircraft, and use of non-intersecting runways are special cases of multiple occupancy of the runway system. However, because of the very strict definition of "runway" in current ATC practice, it may make sense to consider these a separate strategy. It is clear that to fully implement this fourth strategy, improvements in the ATC system are required to permit aircraft streams to operate in such close proximity.

The interaction between the first three strategies is illustrated in Figure 5.1, which shows the effect of changing arrival runway occupancy time on runway capacity under specified conditions. It is clear from the figure that with mixed arrivals and departures under current conditions, with today's ATC system and average runway occupancy times of the order of 50 seconds, neither changing spacing and speed differentials to create a homogeneous mix (aircraft all behave like B-727s) nor changing the runway occupancy gives much benefit. Improving the ATC system to reduce approach spacing by one mile for each aircraft class gives approximately a 20 percent increase in capacity. However, if the average runway occupancy time is also reduced to 30 seconds, the benefit from improving the ATC system increases to a 25 percent improvement in capacity, while changing speed and spacing differentials can produce up to a 20 percent improvement in capacity. If all three strategies are

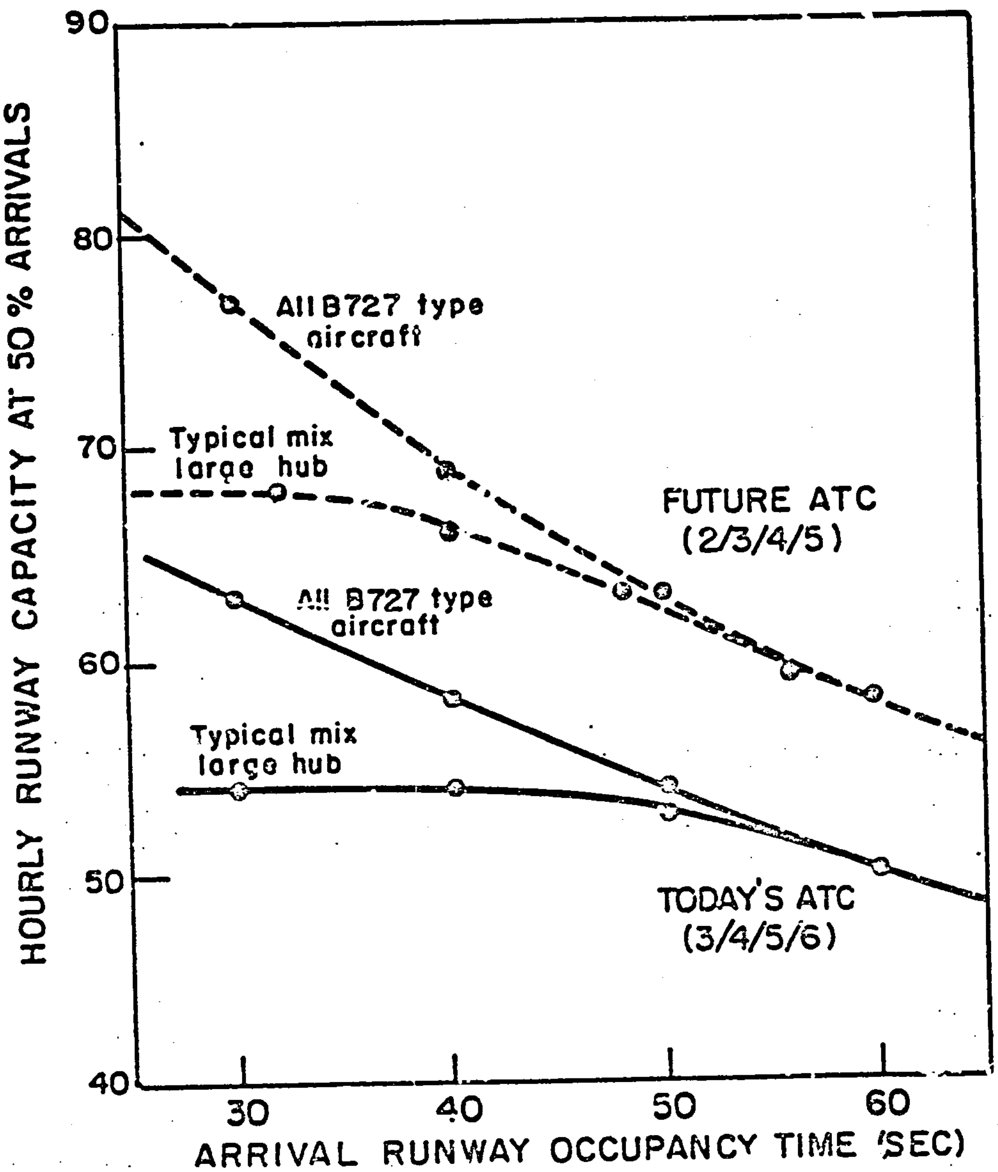


FIG. 5.1 IFR Capacity as a Function of Runway Occupancy Time and ATC Technology--Mixed Operations.

implemented together, the improvement could be as great as a 45 percent increase in capacity.

Therefore it is a combination of the strategies that gives the highest benefit. The first three strategies together give over twice the capacity improvement of any one strategy considered alone and nearly twice the improvement of the best two strategies combined. The second strategy, on which a great deal of research effort has been expended in recent years, appears to be almost worthless in today's ATC environment without the results of the third.

It also became apparent in the course of the study that the interaction between approach speed, aircraft spacing on approach, and the headway between aircraft arrivals at the threshold is extremely important. Runway capacity is the inverse of the average headway between aircraft using the runway, therefore reducing the headway will increase capacity. However, for a given spacing on approach, the headway is a function of the approach speed. Thus if spacing between aircraft on approach is the critical safety determinant, then headways can be reduced by increasing approach speeds, subject to runway occupancy constraints.

Improving aircraft runway occupancy characteristics emerges as an essential prerequisite of other measures to significantly increase runway capacity.

<u>Strategies for reducing runway occupancy</u>

Six promising packages of innovations emerged from the analysis of individual innovations:

- Improved short-haul aircraft technology
- Pilot and airline motivation and regulation
- Improved pilot and controller information flow
- Runway exit and entrance design
- Dense airfield geometry
- Integrated landing management.

Analysis of these packages suggests that, under specified conditions, they would give increases in runway capacity ranging up to 10 percent, or more. These relatively small capacity increases are derived from substantial reductions in runway occupancy time (ranging from 10 to 30 seconds) that resulted from the improvement packages. Figure 5.1 illustrates this relationship.

The packages giving the greatest reduction in runway occupancy time were runway exit and entrance design, followed by short-haul aircraft technology, with runway occupancy time reductions of up to 30 and 25 seconds respectively. Integrated landing management, while having no direct impact on runway occupancy time, could give increases in capacity of the order of 10-40 percent.

Technology and E & D requirements

In developing the various packages of innovations, the research identified a number of improvements in aircraft technology or air traffic control engineering and development measures that either appear to offer significant benefits in reducing the constraint of runway occupancy time on capacity or are required as part of a specific innovation package.

Aircraft technology improvements. Changes in aircraft technology that would contribute to reduced runway occupancy time involve measures to increase the deceleration and acceleration on the runway or to rapidly restore climb power in a go-around situation, measures to permit lower touchdown speeds, or measures to improve the low-speed handling characteristics during final approach and improve handling characteristics on the runway. Specific improvements include:

- Increased thrust-to-weight ratio
- Rapid engine spool-up from idle to climb power
- Enhanced braking performance
- Enhanced exit turn capability
- Increase in available aerodynamic drag on final approach and roll-out
- Use of airborne reverse thrust
- Reduced approach and touchdown speeds using STOL-technology
- Use of active controls to reduce the airspeed/stall-speed margin during final approach or go-around.

The concept of active integration of the flight controls with the power settings and flap/airbrake deployment to improve handling characteristics in critical situations can be used to avoid inadvertent stalls under the tighter safety margins proposed, or to maintain stability on the runway, especially during high-speed exits.

Due to the cost penalty associated with these measures it appears reasonable to target their implementation toward short-haul aircraft, where the en-route penalty is not such a significant proportion of the total operating cost, and where the benefits to be derived from improved performance on the runway occur more frequently.

<u>ATC engineering and development requirements.</u> Many of the proposed innovation packages require or propose new technology to assist in the guidance, control and monitoring of aircraft on final approach or the runway itself. This technology includes the following equipment:

- Automated headway display system
- Aircraft deceleration profile guidance
- Real-time aircraft path generator
- Aircraft runway performance prediction
- Dynamic exit lighting system
- Dynamic airfield sectorization and lighting
- Automated departure release and go-around advisory system
- Headway aircraft sequencing system.

In addition the need for new or improved design criteria has been identified for the following:

- Exit taxiway location
- High speed exit taxiway geometry
- Continuous runway exits

- High speed runway entrance taxiways.

<u>Promising innovations</u>

Many of the innovations proposed are clearly long-term measures, while others offer the opportunity to obtain runway occupancy improvements in the shorter term.

Short term measures that could be implemented within the existing airfield geometry and with the existing aircraft fleet, and that appear to offer significant benefits in relation to the resources required for their implementation, include:

- Improved pilot and controller information through the introduction of such developments as
  - Aircraft deceleration profile guidance
  - Automated headway display system
  - Automated runway performance prediction
  - Automated departure release and go-around advisory system.

  These developments could be implemented separately or as an integrated package.

- Runway exit and entrance design, including
  - Exit taxiway location
  - High speed exit taxiway geometry
  - High speed runway entrance taxiways.

- Pilot and airline motivation through economic incentives to utilize the runway capacity efficiently.

In the longer term, major improvements could be implemented in the aircraft fleet, the procedures used to manage the flow of traffic through the final approach airspace and onto the runway, and in the airport configuration. Measures which appear to offer significant potential for reducing runway occupancy constraints in each of these areas consist of:

- Improved short-haul aircraft technology, especially
  - Enhanced deceleration and acceleration
  - Enhanced exit turn capability.
- Integrated landing management, balancing aircraft speed and spacing to give maximum runway capacity.
- Dense airfield geometry, including
  - Use of taxiways as runways
  - Dynamic airfield sectorization
  - Close parallel and short-runways, including use of part of conventional intersecting runways.

The research has identified many promising innovations, and described the technology required to implement them. It is clear that much of the required technology does not presently exist, and that its development will require further research. As this section has indicated, the potential benefits from reducing the constraint of runway occupancy time on runway capacity are not only substantial, but essential to realize the full benefits of other measures now being taken or planned to address constraints imposed by the current ATC system or aircraft operating characteristics.

FURTHER RESEARCH REQUIREMENTS

The objective of this study was to identify as broad a range of potential innovations as possible, and to evaluate these innovations using information obtained from existing data sources on runway occupancy. Given the resources available, the scope of this evaluation was necessarily limited.

In the course of the project a rich data base was assembled from a number of previous studies. These data were subject to exploratory analysis, but the limited resources constrained how much could be reduced and analyzed. Enough analysis was performed to realize that the runway occupancy process is still poorly understood, and that the data sources identified are deserving of further study. At the same time it was also realized that the existing data was very weak in two important areas:

1. The field data sources available had very little IFR or wet runway conditions.

2. The data sources tended to concentrate either on the airborne or on the runway portion of the process, making investigation of the influence of conditions during the approach on the roll-out and choice of exit very difficult. Most of the principal data sources were strictly plan-position data, with limited height information.

Given the limitations on the ability to model the landing process and the large number of innovations to be evaluated, the evaluations were based on some very general assumptions and arbitrary conditions. Further work on each of the innovations needs to refine and elaborate the concept, and develop a more detailed feasibility analysis.

The following steps need to be performed in order to establish the feasibility of implementing any of the innovations identified in this study:

- Select priority packages for further development
- Evaluate potential benefits and impacts at selected airports
- Develop estimates of development, implementation, and operational costs
- Perform cost-effectiveness evaluation
- Explore operational feasibility.

Once the priority packages have been selected, it will be necessary to develop the concepts contained in the packages in more detail. Research may be required to establish the technical feasibility of particular aspects, and to develop the performance parameters to be used in subsequent analyses.

The evaluation performed to date in this study has investigated the innovations in the context of a 'typical' airport. In order to assess the likely magnitude of benefits and impacts in practice, the innovations should be evaluated in the context of a selected number of major hub airports. These benefits and impacts can probably not be assessed without the improved understanding of the landing process described above.

This study did not attempt to estimate, except in very general terms, the costs associated with developing, implementing, and operating a specific innovation. Considerable further research will be required to be able to develoo these estimates.

The cost-effectiveness evaluation will be based on the results of the previous two tasks. The exploration of operational feasibility will also have to be site-specific and circumstance-specific, and would involve discussions with, and input from, all interested parties, such as airlines, pilots, airport authorities, airframe manufacturers, and government agencies. While preliminary discussions with these parties would be helpful to the conduct of any further research, it is unlikely that substantive progress toward implementation can be achieved until the detailed results of the previous analyses are available for consideration.

SUMMARY

A large number of potential innovations are available to reduce the constraint on runway capacity imposed by runway occupancy. Preliminary analysis suggests that reductions in runway occupancy times of up to 30 seconds and gains in runway capacity of up to 40 percent are achievable. Without these gains, runway occupancy will constrain the increase in runway capacity that would otherwise be obtained from other means.

The landing process is still insufficiently understood to be able to confidently predict the benefits of particular innovations. Existing data require further analysis, and some new data are required for which revised data collection methods are necessary. Much further work remains on developing the various innovations identified in this study and investigating their cost-effectiveness and implementational feasibility.

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APPENDIX A

Extract from FAA Order

"Air Traffic Control"

7110.65B Change 4 1/1/81

Section 2. APPLICATION OF AIR TRAFFIC CONTROL SERVICE

10. ATC SERVICE

Provide air traffic control service in accordance with the procedures and minima in this handbook except when:

a. Deviation is necessary to conform with ICAO Documents, National Rules of the Air, or special agreements where the United States provides air traffic control service in airspace outside the United States and its possessions.

10.a. Note.—Pilots are required to abide by FARs or other applicable regulations regardless of the application of any procedure or minima in this handbook.

b. Other procedures/minima are prescribed in a Letter of Agreement, an FAA or military document.

10.b. Note.—These procedures may include altitude reservations, air refueling, and fighter interceptor operations.

10.b. Reference.—Procedural Letters of Agreement, 12.

11. CONSTRAINTS GOVERNING SUPPLEMENTS AND PROCEDURAL DEVIATIONS

a. Exceptional or unusual requirements may dictate procedural deviations or supplementary procedures to this handbook. Prior to implementing supplemental or any procedural deviation which alters the level, quality, or degree of service, obtain prior approval from the Director, Air Traffic Service.

b. If military operations are involved, it will require the approval of one or more of the following headquarters as appropriate:

U.S. Navy:	CNO (OP-513)
U.S. Air Force:	AFXOOTF
U.S. Army:	Director, USAATCA—Aeronautical Services Office (CCQ-ASO-AT), Cameron Station, Alexandria, Virginia 22314

11. Note.—*TERMINAL:* Headquarters USAF has delegated to major air commands authority to authorize base commanders to reduce same runway separation standards for military aircraft. These are specified and approved by affected ATC and user units. When applied, appropriate advisories may be required; e.g., "(Ident) continue straight ahead on right side; F-16 landing behind on left." "(Ident) hold position on right side; F-5 behind on left."

12. PROCEDURAL LETTERS OF AGREEMENT

Procedures/minima which are applied jointly or otherwise require the cooperation or concurrence of more than one facility/organization must be documented in a Letter of Agreement. Letters of Agreement only supplement this handbook. Any minima they specify must not be less than that specified herein unless appropriate military authority has authorized application of reduced separation between military aircraft.

12. Reference.—7210.3—430, Letters of Agreement.

13. USE OF MARSA

a. MARSA may only be applied to special military operations specified in a Letter of Agreement or other appropriate FAA or military document.

13.a. Note.—Application of MARSA is a military command prerogative. It will not be invoked indiscriminately by individual units or pilots. It will be used only for special IFR operations requiring its use. Commands authorizing MARSA will ensure that its implementation and terms of use are documented and coordinated with the control agency having jurisdiction over the area in which the operations are conducted. Terms of use will assign responsibility and provide for separation among participating aircraft.

b. ATC facilities do not invoke or deny MARSA. Their sole responsibility concerning the use of MARSA is to provide separation between military aircraft engaged in MARSA operations and other nonparticipating IFR aircraft.

14. MILITARY PROCEDURES

Military procedures in the form of additions, modifications, and exceptions to the basic FAA procedure are prescribed herein when a common procedure has not been attained or to fulfill a specific requirement. They shall be applied by:

a. ATC facilities operated by that service.

14.a. Examples.—

An Air Force facility providing service for an Air Force Base would apply USAF procedures to all traffic regardless of class.

A Navy facility providing service for a Naval Air Station would apply USN procedures to all traffic regardless of class.

b. ATC facilities, regardless of their parent organization (FAA, USAF, USN, USA), supporting a designated military airport exclusively. This designation determines which military procedures are to be applied.

14b. Examples.—

An FAA facility supports a USAF Base exclusively—USAF procedures are applied to all traffic at that base.

An FAA facility provides approach control service for a Naval Air Station as well as supporting a civil airport—Basic FAA procedures are applied at both locations by the FAA facility.

A USAF facility supports a USAF Base and provides approach control service to a satellite civilian airport—USAF procedures are applied at both locations by the USAF facility.

14b. Reference.—Annotations, 3.

c. Other ATC facilities when specified in a Letter of Agreement.

14c. Example.—

A USAF Unit is using a civil airport supported by an FAA facility—USAF procedures will be applied as specified in a Letter of Agreement between the unit and the FAA facility to the aircraft of the USAF Unit. Basic FAA procedures will be applied to all other aircraft.

15-20. RESERVED

Section 11. DEPARTURE SEPARATION

1110. SAME RUNWAY SEPARATION

Separate a departing aircraft from a preceding departing or arriving aircraft using the same runway by ensuring that it does not begin takeoff roll until:

1110. Reference.—Wake Turbulence, 1420.

a. The other aircraft has departed and crossed the runway end or turned to avert any conflict. If you can determine distances by reference to suitable landmarks, the other aircraft need only be airborne if the following minimum distance exists between aircraft:

(1) When only Category I aircraft are involved—*3,000 feet.*

(2) When a Category I aircraft is preceded by a Category II aircraft—*3,000 feet.*

(3) When either the succeeding or both are Category II aircraft—*4,500 feet.*

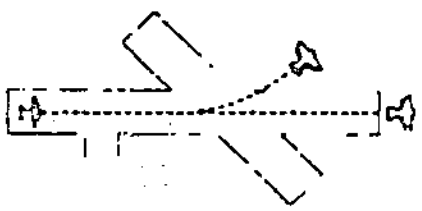
(4) When either is a Category III aircraft—*6,000 feet.*

1110.a. Note.—Aircraft Categories are as follows:

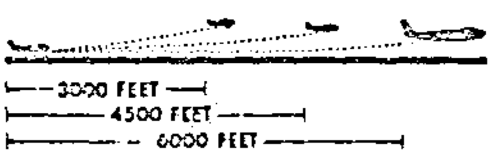
Category I—Light-weight, single-engine, personal-type propeller driven aircraft. (Does not include higher performance, single-engine aircraft such as the T-28.)

Category II—Light-weight, twin engine, propeller driven aircraft weighing 12,500 pounds or less such as the Aero Commander, Twin Beechcraft, DeHavilland Dove, Twin Cessna. (Does not include such aircraft as a Lodestar, Learstar, or DC-3.)

Category III—All other aircraft such as the higher performance single-engine, large twin-engine, four engine, and turbojet aircraft.

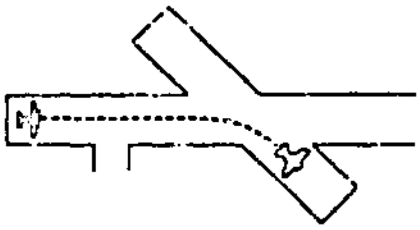


1110.a. Illustration 1



1110.a. Illustration 2

b. A preceding landing aircraft has taxied off the runway.



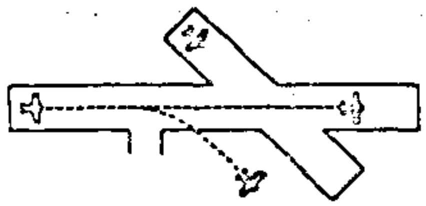
1110.b. Illustration

1111. INTERSECTING RUNWAY SEPARATION

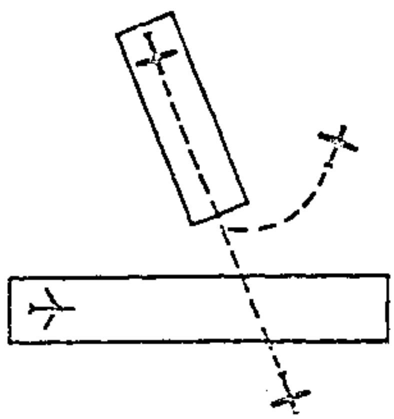
Separate departing aircraft from an aircraft using an intersecting runway, or nonintersecting runways when the flight paths intersect, by ensuring that the departure does not begin take-off roll until one of the following exists:

1111. Reference.—Wake Turbulence, 1426.

a. The preceding aircraft has departed and passed the intersection, has crossed the departure runway, or is turning to avert any conflict.

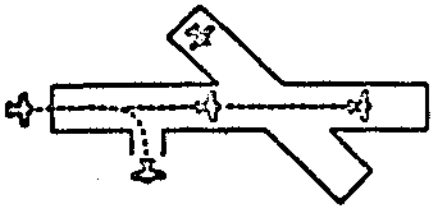


1111.a. Illustration 1

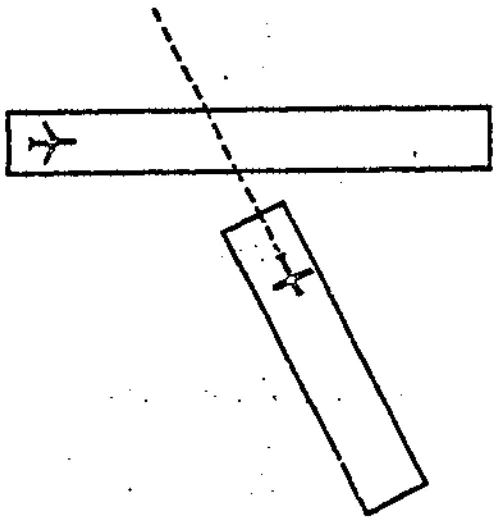


1111.a. Illustration 2

b. A preceding arriving aircraft has taxied off the landing runway, completed the landing roll and will hold short of the intersection, passed the intersection, or has crossed over the departure runway.



1111.b. Illustration 1



1111.b. Illustration 2

1112. ANTICIPATING SEPARATION

Takeoff clearance need not be withheld until prescribed separation exists if there is a reasonable assurance it will exist when the aircraft starts takeoff roll.

→ 1113. INTERSECTION TAKEOFF SEPARATION

a. Separate a Category I or II aircraft taking off from an intersection on the same runway (same or opposite direction takeoff) behind a preceding departing nonheavy Category III aircraft by ensuring that it does not start takeoff roll until at least *3 minutes* after the Category III aircraft has taken off. Inform an aircraft when it is necessary to hold in order to provide the required *3-minute* interval.

Phraseology:
HOLD FOR WAKE TURBULENCE.

b. The *3-minute* interval is not required when:

(1) A pilot has INITIATED a request to deviate from that interval, or

(2) *USA/USAF NOT APPLICABLE.* The intersection is 500 feet or less from the departure point of the preceding aircraft and both aircraft are taking off in the same direction.

1113.b.(1) Note.—A request for takeoff does not initiate a waiver request; the request for takeoff must be accomplished by a request to deviate from the *3-minute* interval.

c. When applying the provisions of b.:

(1) Issue a wake turbulence advisory before clearing the aircraft for takeoff.

(2) Do not clear the intersection departure for an immediate takeoff.

(3) When applying b. (1) or b. (2) above, issue a clearance to permit the trailing aircraft to deviate from course enough to avoid the flight path of the preceding nonheavy Category III departure.

(4) Separation requirements in accordance with 1110.a. must also apply.

1113. Reference.—Wake Turbulence, 911; Intersection Takeoff, 933; Aircraft Categories, 1110.a. Note; Intersection Departure Minima, 1404 (Heavy Jet).

1114. OPPOSITE DIRECTION MINIMA

Separate a Category I or II aircraft behind a nonheavy Category III aircraft taking off or making a low/missed approach when utilizing opposite direction takeoffs on the same runway by *3 minutes* unless a pilot has INITIATED a request to deviate from the *3-minute* interval. In the latter case, issue a wake turbulence advisory before clearing the aircraft for takeoff.

1114. Note.—A request for takeoff does not initiate a waiver request; the request for takeoff must be accompanied by a request to deviate from the *3-minute* rule.

1114. Reference.—Wake Turbulence, 911; Aircraft Categories, 1110.a. Note; Opposite Direction Minima, 1402 (Heavy Jet).

a. Inform an aircraft when it is necessary to hold in order to provide the required *3-minute* interval.

Phraseology:
HOLD FOR WAKE TURBULENCE.

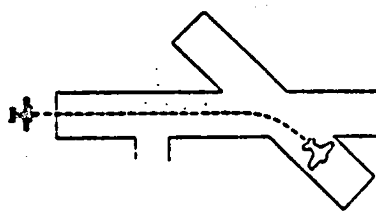
1115–1119. RESERVED

Section 12. ARRIVAL SEPARATION

1120. SAME RUNWAY SEPARATION

Separate an arriving aircraft from another aircraft using the same runway by ensuring that the arriving aircraft does not cross the landing threshold until one of the following conditions exists or unless authorized in 1102.:

a. The other aircraft has landed and taxied off the runway. Between sunrise and sunset, if you can determine distances by reference to suitable landmarks and the other aircraft has landed, it need not be clear of the runway if the following minimum distance from the landing threshold exists:



1120.a. Illustration

(1) When a Category I aircraft is landing behind a Category I or II—*3,000 feet.*

1120.a.(1) Illustration

(2) When a Category II aircraft is landing behind a Category I or II—*4,500 feet.*

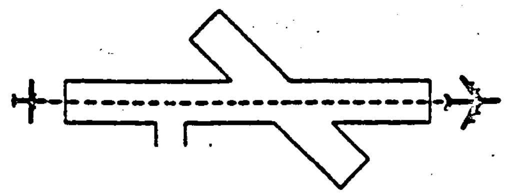
1120.a.(2) Illustration

b. The other aircraft has departed and crossed the runway end. If you can determine distances by reference to suitable landmarks and the other aircraft is airborne, it need not have crossed the runway end if the following minimum distance from the landing threshold exists:

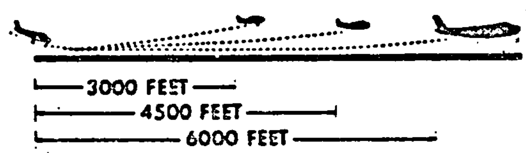
(1) Category I aircraft landing behind Category I or II—*3,000 feet.*

(2) Category II aircraft landing behind Category I or II—*4,500 feet.*

(3) When either is a category III aircraft—*6,000 feet.*



1120.b. Illustration 1



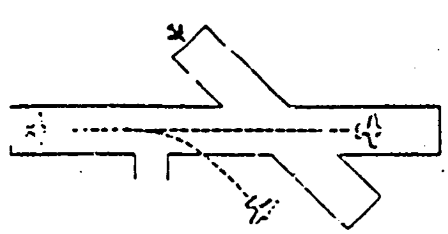
1120.b. Illustration 2

1121. INTERSECTING RUNWAY SEPARATION

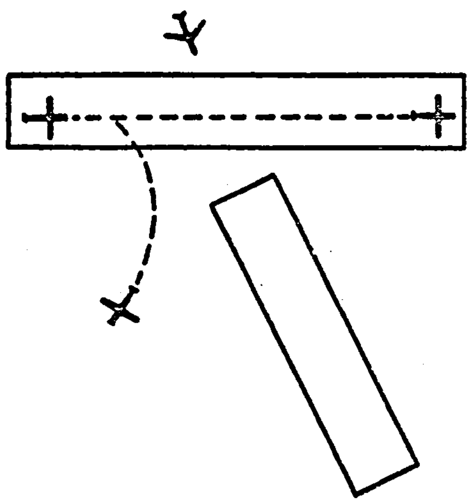
a. Separate an arriving aircraft using one runway from another aircraft using an intersecting runway or a nonintersecting runway when the flight paths intersect by ensuring that the arriving aircraft does not cross the landing threshold or flight path of the other aircraft until one of the following conditions exists:

1121.a. Reference.—Wake Turbulence, 1425.

(1) The preceding aircraft has departed and passed the intersection/flight path or is airborne and turning to avert any conflict.

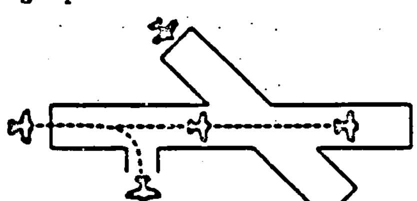


1121.a.(1) Illustration 1

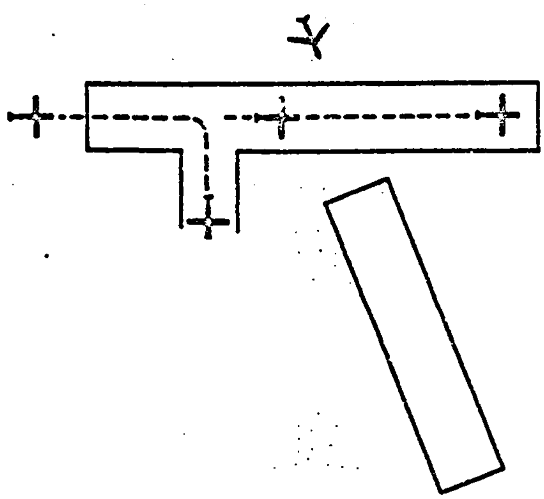


1121.a.(1) Illustration 2

(2) A preceding arriving aircraft has taxied off the landing runway, completed landing roll and will hold short of the intersection/flight path, or has passed the intersection/flight path.



1121.a.(2) Illustration 1



1121.a.(2) Illustration 2

b. *USAF/USN NOT APPLICABLE.* When approved by the facility chief in accordance with the provisions of 7210.3-1227, authorize simultaneous landings on intersecting runways only when the following conditions are met:

(1) The runway/s to be used are dry and you have received no reports that braking action is less than good on both runways.

(2) Operations are conducted in VFR conditions unless visual separation is applied to aircraft conducting simultaneous landings.

(3) Instructions are issued to restrict one aircraft from entering the intersecting runway/s to be used by another aircraft. Where operational benefit is not a factor, restrict the landing aircraft in the lesser group from entering the intersection.

(4) Traffic information is issued to and an acknowledgement received from both aircraft involved.

(5) The measured distance from the landing threshold to intersection is issued if requested by either aircraft.

(6) The conditions specified in (3), (4), and (5) are met at or before landing clearance is issued and in sufficient time for the pilots to take other action if desired.

(7) Group 1 aircraft are operating in accordance with a Letter of Agreement with the aircraft operator/pilot or you ascertain from the pilot that it is a STOL aircraft.

(8) The aircraft group is known (Appendix 3) and the distance from landing threshold for the aircraft being instructed to hold short is in accordance with Facility Directives and diagrams.

1121.b. Examples.—

"After landing, taxi south on Runway One Eight, hold short of Runway Niner Left."

"Cleared to land, Runway One Eight, six thousand feet available, hold short of Runway Two Two, traffic landing Two Two."

"Cleared to land Runway One Four Left, traffic landing runway One Eight will hold short of Runway One Four Left."

1121.b. Note.—If a pilot prefers to use the full length of the runway or a runway different from that specified, he is expected to advise ATC prior to landing.

1121.b.(8) Reference.—7210.3-1227, Aircraft Group/Distance Minima Table.

Section 7. SEA LANE OPERATIONS

1520. APPLICATION

Where Sea Lanes are established and controlled, apply the provisions of this section in lieu of the procedures contained in **Chapter 5, Sections 11 and 12.**

1521. DEPARTURE SEPARATION

Separate a departing aircraft from a preceding departing or arriving aircraft using the same sea lane by ensuring that it does not commence takeoff until:

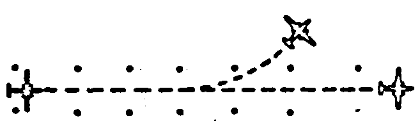
a. The other aircraft has departed and crossed the end of the sea lane or turned to avert any conflict. If you can determine distances by reference to suitable landmarks, the other aircraft need only be airborne if the following minimum distance exists between aircraft:

(1) When only Category I aircraft are involved—*1,500 feet.*

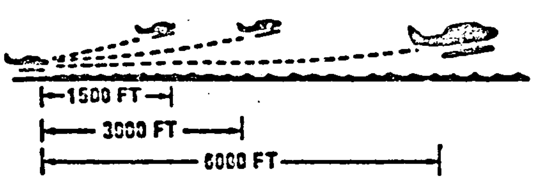
(2) When a Category I aircraft is preceded by a Category II aircraft—*3,000 feet.*

(3) When either the succeeding or both are Category II aircraft—*3,000 feet.*

(4) When either is a Category III aircraft—*6,000 feet.*



1521.a. Illustration 1.



1521.a. Illustration 2.

b. A preceding landing aircraft has taxied out of the sea lane.

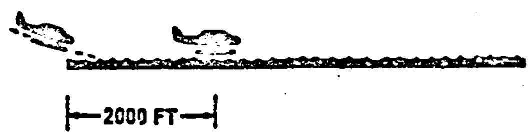
1521. Note.—Due to the absence of braking capability, caution should be exercised when instructing a float plane to hold a position as the aircraft will continue to move because of prop generated thrust. Clearance to taxi into position and hold should, therefore, be followed by takeoff or other clearance as soon as practicable.

1522. ARRIVAL SEPARATION

Separate an arriving aircraft from another aircraft using the same sea lane by ensuring that the arriving aircraft does not cross the landing threshold until one of the following conditions exists:

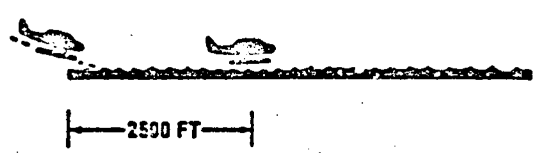
a. The other aircraft has landed and taxied out of the sea lane. Between sunrise and sunset, if you can determine distances by reference to suitable landmarks and the other aircraft has landed, it need not be clear of the sea lane if the following minimum distance from the landing threshold exists:

(1) When a Category I aircraft is landing behind a Category I or II—*2,000 feet.*



1522.a.(1) Illustration.

(2) When a Category II aircraft is landing behind a Category I or II—*2,500 feet.*



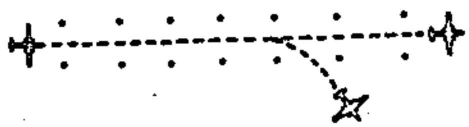
1522.a.(2) Illustration.

b. The other aircraft has departed and crossed the end of the sea lane or turned to avert any conflict. If you can determine distances by reference to suitable landmarks and the other aircraft is airborne, it need not have crossed the end of the sea lane if the following minimum distance from the landing threshold exists:

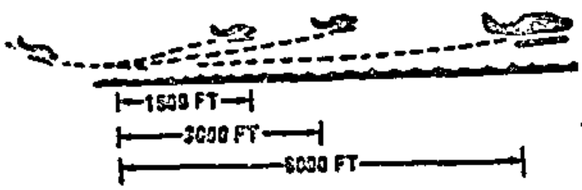
(1) When only Category I aircraft are involved—*1,500 feet.*

(2) When either is a Category II aircraft—*3,000 feet.*

(3) When either is a Category III aircraft—*6,000 feet.*



1522.b. Illustration 1.



1522.b Illustration 2.

1523-1529. RESERVED

APPENDIX B

Extract from FAA Order

"Facility Operation and Administration"

7210.3E Change 5 10/9/80

(2) If there is a system failure rendering the LLWSAS unusable, notify Airway Facilities and NOTAM the system out of service.

c. Airway Facilities is responsible for verification of the accuracy of the LLWSAS. The local sector will notify Air Traffic of any equipment that is out of tolerance.

1223. RELAY OF RVV/RVR VALUES

a. Relay of RVV/RVR values from the weather observing facility to the control tower may be discontinued at the request of the tower when there is no traffic activity at that specific location.

b. Establish relative priorities on the visibility information at locations with two or more RVR or RVV runways where data is required for two or more runways.

1224. APPROACHING SEVERE STORM ACTIVITY

a. AT personnel shall monitor weather reports and radar to determine when severe storm activity is approaching a facility's area.

b. After coordination with the AT facilities concerned, AF personnel will place the facility on standby power. Engine generators will be kept on until the storm activity has dissipated.

1225. ADVANCE APPROACH INFORMATION

Where more than one position could issue the data, assign responsibility for issuing advance approach information to a specific position in a Facility Directive. Display the information so that it is readily accessible to the controller having need for it.

1226. ILS HEIGHT/DISTANCE LIMITATIONS

An ILS is normally flight checked to 4,500 feet and 18 miles for the localizer and 4,500 feet and 10 miles for the glide slope. If an operational need to exceed these limitations exists, inform FIFO and they will flight check the ILS to the stipulated requirement. Ensure that current flight check data are available to facility personnel.

1227. SIMULTANEOUS LANDINGS ON INTERSECTING RUNWAYS

a. Should a facility chief determine a valid operational need exists to conduct simultaneous landings on intersecting runways, facility directives, diagrams, and tables shall then be prepared which direct the handling of these landings.

b. Prepare an airport diagram showing the measured distance from runway threshold to the intersection for the runway involved. Measure this distance from the landing threshold to the nearest edge of the intersecting runway.

c. Aircraft group/runway distance criteria shall be established using 7110.65, Appendix 3, and the following table:

AIRCRAFT GROUP/DISTANCE MINIMA TABLE

	Sea Level 999	*1,000 1,999*	*2,000 2,999*	*3,000 3,999*	*4,000 4,999*	*5,000 5,999*	*6,000 6,999*	*7,000 Above*
GROUP 1	1 650	1,700	1,750	1,800	1,850	1,900	1,950	2,000
GROUPS 1 & 2	3,000	3,050	3,100	3,150	3,200	3,250	3,300	3,350
GROUPS 1, 2, & 3	4,500	4,550	4,600	4,650	4,700	4,750	4,800	4,850
GROUPS 1, 2, 3, & 4	6,000	6,100	6,200	6,300	6,400	6,500	6,900	7,000
GROUPS 1, 2, 3, 4, & 5	8,000	8,100	8,200	8,300	8,400	8,500	8,600	8,700
GROUPS 1, 2, 3, 4, 5, & 5A	8,400	8,600	8,800	8,900	9,200	9,500	9,700	10,000

1228-1229. RESERVED

APPENDIX C

Appendix 3 Extracted from FAA Order

"Air Traffic Control"

7110.65B Change 4 10/2/80

Appendix 3. AIRCRAFT WEIGHT CLASSES AND GROUPS

Manufacturer/Model	Type Designator Civil	Type Designator Military	Weight Class/ Group
Aeronca (USA)			
Aeronca Champion	AR58		S/2
Chief/Super Chief	AR11		S/2
Sedan	AR15		S/2
Aero Spacelines (USA)			
Guppy	AP52		L/5
Mini Guppy	AP3M		L/5
Pregnant Guppy	AP[illegible]P		L/5
Super Guppy/ Turbine	AP25/AP45		L/5
Aerospatiale (France)			
Caravelle	S210		L/4
Concorde	CONC		H/5
Corvette SN601	S601		L/3
Rallye MS 880/881/883	S880		S/3
Rallye Commodore MS 892	S892		S/2
Rallye Minerva MS 894	S894		S/2
Airbus Industrie (International)			
Airbus	A300		H/5
Alon, Inc. (USA)			
Aircope A2	F02		S/2
Andrie Tupolev (USSR)			
Tu-114	TU114		H/5
Tu-144	TU144		H/5
Antonov (USSR)			
AN-10	AN10		L/4
AN-12	AN12		L/5
Avro (A.V. Roe) (U.K.)			
Anson	AV52		L/3
CF-100		CF00	L/4
Lancaster	LANC		L/4
Shackleton		SHC3	L/4
Beagle Aircraft (U.K.)			
Airdale	BT10		S/2
Model 206S	BT6S		S/3
Beech Aircraft (USA)			
Airliner	BE99		S/2
Baron	BE55	T42	S/2
Baron 58	BE58		S/2
Bonanza 33	BE33		S/2
Bonanza 35	BE35		S/2
Bonanza 36	BE36		S/2
Duke	BE60		S/3
Duchess	BE76		S/2
King Air 90	BE90	U21	S/2
King Air 100	BE10		S/3
Mentor	BE45	T34	S/2
Queen Air 65/A65/70	BE65		S/2
Queen Air 89	BE80		S/2
Seminole		U8	S/2
Sierra 24	BE24		S/2
Sport 19	BE19		S/2
Stagger Wing	BE17		S/2
Sundowner	BE23		S/2
Super H18	BE8S		S/2
Super King Air 200	BE20		S/3
Super Queen 88	BE88		S/2
Travelair	BE95		S/2
Twin Beech 18	BE18	C45	S/2
Twin Bonanza	BE50		S/2
Bellanca Aircraft (Includes Downer/ Northern) (USA)			
Citabria	CH10		S/2
Citabria 7ECA	CH9		S/2
Cruisair Sr./Cruise-master 14-19	BL14		S/2
Decathlon	BL30		S/2
Scout	BL28		S/2
Viking	BL26		S/2
Boeing Aircraft (USA)			
707 100/200	B707		L/5
707 300/400	H/B707		H/5
720	B720		L/5
720B	B72S		L/5
727	B727		L/4
737	B737	T43	L/4
747	B747	E4A	H/5A
747SP	B74S		H/5
767	B767		H/5
AWACS		E3A	H/5
EC135		E135	L/5
Stearman	B75		S/2
Stratofortress		B52	H/5
Stratofreighter		KC97	L/4
Stratolifter B717		C135	L/5
Stratotanker KC135		KC135	L/6
VC37B		C137B	L/5
VC37C		C137C	H/5
YC14		YC14	L/4
Bristol Aircraft (U.K.)			
Britannia 310	BR31		L/5

Manufacturer/Model	Type Designator Civil	Type Designator Military	Weight Class/Group
British Aerospace Corp. (U.K.)			
BAC 111	BA11		L/4
Harrier		AV8*	L/4
HS/DH 125-600/700	HS25		L/3
HS 743 Series	HS748		L/4
Super VC 10	BA15	VC15	H/5
Trident	HS21		L/4
Vanguard	VC9		L/4
VC 10	BA10	VC10	H/5
Viscount	VC7		L/4
Vulcan		VLCN	H/4
Britton Norman Ltd. (U.K.)			
Islander	BN2		S/2
Trislander-Mark 3	BN3		S/2
Bushmaster Aircraft Corp. (USA)			
Bushmaster 2000	BU20		L/3
Camair (USA)			
Model 480 (Twin Navion)	CM48		S/3
Yukon	CC06		L/4
Candair Ltd. (Canada)			
Argus	CL28	CP07	L/4
Challenger	CL60		L/4
Cosmopolitan, (Convair 540)	CL66/CV54	CC09	L/4
North Star	NSTR		L/4
Starfighter	CF04	F104*	L/5
Yukon (Freightliner)	CL44	CC06	L/5
Cessna Aircraft (USA)			
120	C120		S/2
140	C140		S/2
150	C150		S/2
152	C152		S/2
170	C170		S/2
172 Skyhawk	C172	T41	S/2
175 Skylark	C175		S/2
177 Cardinal	C177		S/2
180	C180		S/2
182	C182		S/2
185 Skywagon	C185		S/2
188 Agwagon	C188		S/2
190	C190		S/2
195	C195		S/2
205	C205		S/2
206	C206		S/2
207 Super Skywagon	C207		S/2
210	C210		S/2
305/321 Bird Dog	C305	O1	S/2
310	C310	U3	S/2
318		T37*	S/2
318E Dragonfly		A37*	S/2
320 Skynight	C320		S/2
336 Skymaster	C336		S/2
337 Super Skymaster	C337	O2	S/2
340	C340		S/2
401	C401		S/2
402	C402		S/2
411	C411		S/2
414	C414		S/2
421	C421		S/2
441	C441		S/2
Citation I/II	C500		S/3
Citation III	C50S		S/3
Champion Aircraft Corp. (USA)			
Challenger	CH8		S/2
Lancer 402	CH40		S/2
Traveler/Tri-Traveler	CH7		S/2
Curtis Wright (USA)			
Commando	CW46	C46	L/3
Dassault (France)			
Falcon 10	DA10		L/3
Falcon 20	FFJ		L/3
Falcon 50	DA50		L/3
Mercure	DA01		L/5
Mercure 200	DA02		L/5
DeHavilland (Canada & U.K.)			
Beaver	DH2	U6	S/2
Buffalo	DH5	C8	L/3
Caribou	DH4		L/3
Chipmunk	DH1		S/2
Comet 2	DH62		L/5
Comet 4	DH64		L/5
Dash 7	DH7		L/2**
Dove (Devon)	DH10		S/2
Heron	DH11		S/2
Otter	DH3	U1	S/2
Turbo Beaver	DH2T		S/2
Twin Otter	DH6	U18	S/2
Dornier GmbH (West Germany)			
Dornier 27	DO27		S/3
Dornier 28	DO28		S/3
→ **Embraer** (Brazil)			
Bandeirante	E110		S/4

Manufacturer/Model	Type Designator Civil	Type Designator Military	Weight Class/Group
Fairchild Industries (USA)			
A10		A10A*	S/4
Cornell	FA62		S/2
FH227	FA22		L/3
Friendship F27	FA27		L/3
Flying Box Car	FA24		L/4
Pilatus/Peacemaker	PL6	AV23A	S/1
Provider		C.23	L/4
Thunderchief		F105*	L/5
Fokker-VFW BV (Netherlands) (See VFW-Fokker)			
Foxjet International (USA)			
ST/600	FXJ		S/2
Gates Learjet Corp. (USA)			
23	LR23		S/3
24	LR24		L/3
25	LR25		L/4
35	LR35		L/4
36	LR36		L/4
General Dynamics Corp. (USA)			
Canso/Catalina	CV14	PBSY	L/4
Convair 240	CV24		L/4
Convair 440	CV44		L/4
Convair 580	CV58		L/4
Convair 600	CV60		L/4
Convair 640	CV64		L/4
Convair 880	CV88		L/5
Convair 990	CV99		L/5
Delta Dagger		F102*	L/5
Delta Dart		F106*	L/5
F16A/B		F16*	L/5
F111/FB111		F111*	L/5
Liner/Samaritan	CV34	C131	L/4
Privateer		P4	L/4
Valiant 34	CV13		S/3
Grumman Aerospace Corp. (USA)			
Ag-Cat	G164		S/2
Albatross	G64	U16	L/3
American	AA1		S/2
American Tr-2	AA2		S/2
Cheetah/Tiger	AA5		S/2
Cougar	GA7		S/2
Cougar G93		F9*	L/5
Goose/Super Goose	G21		L/3
Greyhound		C2	L/4
Gulfstream I	G159	VC4	L/4
Gulfstream II	G2	VC11	L/4
Hawkeye		E2	L/5
Intruder		A6*	L/5
Mallard	G73		L/3
Mohawk	G134	OV1	S/3
Tiger		F11*	L/5
Tomcat		F14*	L/5
Tracer		E1	L/4
Tracker	G89	S2	L/4
Trader		C1	L/4
Widgeon/Super Widgeon	G44		L/3
Handley Page (U.K.)			
Jetstream	HP13		S/3
Hamburger Flugzeugbau (West Germany)			
Hansajet	HF32		L/3
Hamilton Aviation (USA)			
Westwind	WSW		S/3
Helio Aircraft Co. (USA)			
Courier	HE1		S/1
Stallion	HE5	AU24	S/1
Super Courier/Tri-Courier	HE3	U10	S/1
Howard Aero Mfg. (USA)			
Model 500 (WARO)	HW5		L/4
Ilyushin (USSR)			
IL-18	IL18		L/5
IL-38	IL38		L/4
IL-62	IL62		H/5
IL-76	IL76		H/5
Israel Aircraft Industries, Ltd. (Israel)			
Arava 101	RV01		L/3
Arava 201	RV02		L/3
Westwind 1123	WW23		L/4
Westwind 1124	WW24		L/4
Lake Aircraft (USA)			
LA-4-200 Buccaneer	LA4		S/2
Learavia Inc. (USA)			
Lear Fan	LRF		S/2
Lockheed Aircraft Corp. (USA)			
Constellation (649)	L649		L/5
Constellation (749)	L749	C121	H/5
Electra	L188		L/4
Galaxy		C5A	H/5

Manufacturer/Model	Type Designator Civil	Type Designator Military	Weight Class/ Group
→ Hercules	L100	C130	L/4
Jetstar	L329	C140	L/4
Lodestar	L18		L/3
Neptune		P2	L/4
Orion		P3	L/4
Reconnaissance		SR71*	L/5
Sea Star		T1*	L/5
Shooting Star		T33*/F80*	L/4
Starfighter		F104*	L/5
Starlifter		C141	H/5
Starliner	L164		L/5
Super Constellation	L49		L/5
Tri-Star	L101		H/5
U2		U2*TR-1*	S/5
Viking		S3A	L/4
YF12A		F12	L/4
Martin Co. (Division of Martin-Marietta Corp.) (USA)			
202	M202		L/3
404	M404		L/3
Canberra		B57*	L/5
Maule (USA)			
M4/5	ML4		S/2
McDonnell-Douglas Aircraft (USA)			
DC-6B	DC6B		L/4
DC-7/7B	DC7		L/5
DC-8	DC8		L/5
DC-9	DC9	C9	L/4
DC-10	DC10		H/5
Eagle		F15*	L/5
Invader		B26	L/4
Liftmaster	DC6	C118	L/4
Phantom II		F4*	L/4
Seven Seas/Speed Freighter	DC7C		L/5
Skyhawk		A4*	L/5
Skymaster	DC4	C54	L/4
Skynight		F101*	L/5
Skyraider		A1*	L/4
Skytrain	DC3	C47	L/3
Skywarrior		A3*	L/4
Super DC3	DC3S	C117	L/3
Super DC8 30/40/50	H/DC8		H/5
Super DC8 61/62/63	DC86		H/5
YC15		YC15	L/3
Messerschmitt (West Germany)			
Monson	ME29		S/2
Mitsubishi (Japan)			
MU2	MU2		S/2
Mooney Aircraft Co. (USA)			
Mark 10	MO10		S/2
Mark 20	MO20		S/2
Mark 21	MO21		S/2
Mark 22	MO22		S/2
Navion Aircraft Co. (USA)			
Range Master	NA1		S/2
Nihon Aeroplane Mfg. Co. (Japan)			
Model YS11	YS11		L/3
Noorduyn Norseman (Canada)			
Norseman MK (IV)	NY4		S/2
Norseman MK (V)	NY5		S/2
Nord Aviation (France)			
Martinet NC701/02		MART	L/3
Nortalrs 25C1		NORD	L/3
Super Broussard-260/262	ND26		L/3
Transall C160	ND16		L/3
Northrop (USA)			
F18		F18*	L/5
Talon		T38*	S/5
Tiger/Freedom Fighter		F5*	L/5
Piaggio & Co. (Italy)			
Royal Gull	P136		S/2
Super Gull	P166		S/2
Vespa Jet	P808		L/3
Pilatus Aircraft (Switzerland)			
Pilatus Porter	PL6		S/1
Turbo Porter	PL6A		S/1
Piper Aircraft (USA)			
Aerostar	PA60		S/2
Apache	PA23		S/2
Aztec	PAZT	U11	S/2
Brave	PA36		S/2
Cherokee	PA28		S/2
Cherokee Arrow (R)	PARO		S/2
Cheyenne	PAYE/42		S/3
Chieftain	PA31		S/2
Clipper	PA16		S/2
Commanche	PA24		S/2

Manufacturer/Model	Type Designator Civil	Type Designator Military	Weight Class/ Group
Cruiser	PA5		S/2
Cub Special	PA11		S/2
Cub Trainer	PA2		S/2
Family Cruiser	PA14		S/2
Lance	PA32T		S/2
Navajo	PA31		S/2
Pacer	PA20		S/2
Pawnee	PA25		S/2
Seminole	PA44		S/2
Seneca	PASE		S/2
Super Cruiser	PA12		S/2
Super Cub	PA18	U7	S/2
Tomahawk	PA38		S/2
Tri-Pacer/Colt Caribbean	PA22		S/2
Twin Comanche	PA30/39		S/2
Vagabond Trainer	PA15		S/2
Vagabond	PA17		S/2
Riley Aeronautics (USA)			
Model 65/Rocket	RY65		S/2
Turbo-Executive	RY40		S/2
Rockwell International (USA)			
Aero Commander 112	AC12		S/2
Aero Commander 685	AC85		S/2
Alt-Cruiser	AC72		S/3
Bronco		OV10*	L/3
Buckeye T-20		T2*	L/5
Commander 112A	AC2A		S/2
Commander 112TC	AC2T		S/2
Commander 114	AC14		S/2
Commander (200)	AC20		S/2
Commander (500)	AC50		S/2
Commander (520)	AC52		S/2
Commander (560)	AC56	U9	S/2
Darter (100/150)	AC10		S/2
Grand Commander (680FL)	AC60		S/2
Jet Commander	AC21		L/3
Lark	LARK		S/2
Mitchell		B25	L/3
Navion	N145		S/2
Sabre		F86*	L/5
Sabreliner		T39	S/3
Sabreliner	N265		L/3
Super Commander (680S)	AC68	U4	S/2
Super Sabre		F100*	L/5
Texan	N6	T6*	S/2
Trojan		T25*	S/2
Turbo Commander	AC6T		S/2
Vigilante		A5*	L/5
Scottish Aviation (U.K.)			
Pioneer	SCP		S/2
Twin Pioneer	SCPT		S/2
Short (U.K.)			
Belfast	SH5	SC5	L/5
Short	SHD3		L/3
Skyvan	SH7		S/3
Silvaire (USA)			
Luscombe	SL8		S/2
Stinson (USA)			
Reliant (Vultee)	ST77		S/2
Voyager/Station Wagon (105/108)	ST75		S/2
Sud Aviation (France)			
Caravelle	S210		L/4
Swearingen Aviation (USA)			
Merlin IIA	SW2		S/3
Merlin IIB	SW3		S/3
Merlin IV/Metro	SW4		S/3
Taylorcraft (USA)			
Sportsman 19	TC19		S/2
Topper 20A	TC20		S/2
Tourist 15A	TC15		S/2
VFW-Fokker (West Germany)			
→ FH227	FK22		L/3
→ Friendship	FK27		L/3
→ Fellowship	FK28		L/4
VFW 614	VF14		L/3
Vought (USA)			
Corsair II		A7*	L/5
Crusader		F8*	L/5
Swift	TE1		S/2

HELICOPTERS

Manufacturer/Model	Type Designator Civil	Type Designator Military	Weight Class/ Group
Aerospatiale (France)			
Lama	HR15		S/1
Alouette II	HR30		S/1
Aloutte III	HR60		S/1
Dauphin	HR35		S/1
Ecureuil/Astar	HR35		S/1
Gazelle	HR34		S/1
Puma	HR33		L/2
Super Frelon	HR32		L/2
Bell Helicopter (Textron) (USA)			
Biglifter	HB14		L/2
Cobra	HB09	AH1	S/1
Jet Ranger	HB47	H58	S/1

Manufacturer/Model	Type Designator Civil	Type Designator Military	Weight Class/ Group
Iroquois	HB04	UH-1H	S/1
Kiowa		OH-58A	S/1
Long Ranger/Sea Ranger	HB06	H57	S/1
Model 205 A-1	HB05		S/1
Sea Cobra		AH-1T	L/2
Sioux	HB13	H13	S/1
Twin Huey	HBTH	UH-1N	S/1
Boeing Vertol Co. (USA)			
Chinook	HV47	CH47	L/2
Model 105	B105		S/1
Sea Knight	HV07	CH46	L/2
Brantley-Hynes Helicopter, Inc. (USA)			
Model B-2A/B-2B	HB42		S/1
Model 305	HB43		S/1
Breda Nardi Costruzioni (Italy)			
Model 269C	NH30		S/1
Model 369D	NH50		S/1
Costruzioni Aeronautiche, Agusta (Italy)			
Model 47T-3B1	A47T		S/1
Model A109	A109		S/1
Model 212 ASW	A212		S/1
Enstrom Corp. (USA)			
Executive	HF28		S/1
Shark	HF20		S/1
Turbo-Shark	HF8C		S/1
Fairchild/Republic (USA)			
L3/SL3	HH3		S/1
L4/SL4	HH4		S/1
Raven	HH12	H23	S/1
Hughes Helicopters Div. of Summa Corp. (USA)			
AAH	HU64	YAH64	L/2
Model 269/300	HU30		S/1
Osage		H55	S/1
Pawnee 369/500	HU50	H6	S/1
Kaman Aircraft Corp. (USA)			
Huskie 600-3/5	HK60	H43	L/2
Seasprite		H2	L/2
Kawasaki Heavy Industries Ltd. (Japan)			
Model BK-117	HK17		S/1
Messerschmitt-Boelkow-Blohm (West Germany)			
Model BO 105	HM05		S/1
Model BK 117 (Kawasaki)	HK17		S/1
Panstwowe Zaklady Lotnicze (Poland)			
Model SM-1W/2	HZ1		S/1
Model Mi-2/2M	HZ2		S/1
Robinson Helicopter, Inc. (USA)			
Model R22	HR22		S/1
Sikorsky Aircraft (USA)			
Black Hawk S-70	SK70	H60	L/2
Chickasaw S-55	SK55	H19	S/1
Choctaw S-58 Seashore/Seabozt	SK58	H34	L/2
Lamps MK3		SH60	L/2
Model S-51	SK51		L/2
Model S-52	SK52		L/2
Model S-59	SK59		L/2
Model S-62	SK62	H52	S/1
Model S-69	SK69	H59	S/1
Model S-76	SK76		S/1
Mojave S-56	SK56	H37	L/2
RSRA S-72	SK72		L/2
Sea King S-61	SK61	H3	L/2
Sea Stallion S-65	SK65	H53	L/2
Skycrane S-64 E/F	SK64		L/2
Tarhe S-64		H54	L/2
Silvercraft (Italy)			
Model SH-4	HS4		S/1

NOTE: The Weight Class listings of this Appendix are to be used for wake turbulence separation purposes only. The aircraft groups are general.

* Indicates single-piloted military turbojet aircraft.

** DeHavilland Dash-7 authorized 2000 feet with Letter of Agreement and 7½° glide slope.

When the weight class cannot be determined from this Appendix, obtain aircraft gross weight from pilot and use the appropriate weight class designator.

Groups are based on FAA certificated stopping distance and/or manufactured published performance data.

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