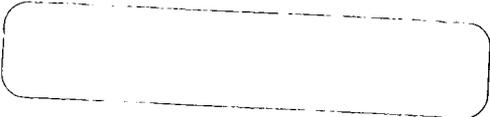


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TRAFFIC ENVIRONMENT
AND
OPERATIONAL PROCEDURES

Final Report on Contract NAS 2-6437

March 1972

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Final Report on Contract NAS 2-6437

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The publication of this report does not constitute approval by the National Aeronautics and Space Administration of the findings or conclusions contained therein. It is published only for the exchange and stimulation of ideas.

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ABSTRACT

The expected traffic environment for an intercity STOL transportation system is examined, and operational procedures are discussed in order to identify problem areas which impact STOL avionics requirements. Factors considered include: traffic densities, STOL/CTOL/VTOL traffic mix, the expected ATC environment, aircraft noise models and community noise impact, flight paths for noise abatement, wind considerations affecting landing, approach and landing considerations, STOLport site selection, runway capacity, and STOL operations at jetports, suburban airports, and separate STOLports.

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EXECUTIVE SUMMARY

Prior to the introduction of a new STOL short-haul transportation service, it is necessary to identify and understand the expected operational environment. Such understanding will aid in establishing STOL avionics requirements. This report examines two aspects of the STOL operating environment. The first, which is called the Traffic Environment, encompasses such factors as STOL demand, the size and mix of vehicles (STOL, CTOL, and VTOL), STOLport location, runway and terminal area capacity, and the air traffic control (ATC) system. The second, entitled Operational Procedures, addresses STOL noise impact, flight path definition, atmospheric effects, and interaction with the final-approach landing aids. Consideration is also given to the ATC problems associated with STOL operations at jetports, suburban airports, and separate STOLports.

It is the intent of the report to provide a better understanding of the STOL operating environment, and to suggest possible solutions to some problem areas. An attempt has been made to identify those problem areas which impact avionics and ground-system requirements. There remain, however, several critical areas (discussed briefly in this summary) requiring significant additional work prior to the introduction of commercial STOL service.

TRAFFIC ENVIRONMENT

The expected traffic environment for an intercity STOL transportation system is examined in order to facilitate the definition of STOL operating procedures and to aid in establishing STOL avionics requirements.

A description of the expected STOL air traffic environment for planning purposes should consider two aspects of STOL air traffic: the characteristics of the traffic — that is, the traffic densities, vehicular types, and the traffic mix expected in various geographical regions at future times — and the control of the traffic in terms of air traffic control procedures and policies.

STOL Traffic Characteristics

Conclusions regarding the potential economic viability of STOL air systems have varied. An interurban STOL air service (the only type to be considered here) may never materialize. However, a number of the economic and system studies conducted over the past six years have depicted a successful interurban STOL air service in which substantial numbers of vehicles are involved. Since the presence of a large number of STOL vehicles in short-haul air service may pose problems for the air traffic control system, the traffic characteristics as depicted in two of these studies are considered further.

The two studies considered are the Northeast Corridor Transportation Project Report¹ and supporting volumes, and the Civil Aeronautics Board's Northeast Corridor VTOL Investigation, specifically the exhibits prepared by de Havilland Aircraft of Canada, Ltd.²

The analyses and data presented with respect to V/STOL systems in the Northeast Corridor Transportation Project Report have been criticized as overly optimistic in a subsequent report issued by the Department of Transportation.³ A particular issue is the cost of providing V/STOL terminals and ATC facilities. The traffic levels cited herein should therefore be regarded as potential traffic levels achievable given sufficient time, rather favorable economic circumstances, and community and passenger acceptance.

It is particularly interesting to note whether any of the terminal sites in the system would be congested at the operations levels anticipated by the Northeast Corridor Transportation Project (listed in Table 2.2-1 of the main report). Different types of terminals are involved: STOLports, large and small general-aviation airports, and airports having a large percentage of air carrier traffic. The Manhattan

STOLport is the busiest, having 280 operations per day in one instance. Assuming a peak-to-average-hour operations ratio of 3 which is typical of air carrier operations at the busier airports, this translates into 35 operations during a peak hour — busy, but not terribly congested. In the case of air carrier airports, the impact of the indicated STOL operations (e.g., 158 operations per day at La Guardia) cannot be assessed without further information about the reductions which have presumably been made possible in short-haul CTOL traffic, and the severity of STOL/CTOL conflicts, a subject which is discussed in the ATC System Interface section of this report. STOL operations at the larger general-aviation airports (e.g., 98 operations per day at Teterboro) are likely to be a problem because of existing congestion at peak hours. The safety of STOL operations at the busier general-aviation airports is also open to question.

Similar data taken from the de Havilland exhibits before the Civil Aeronautics Board are examined in the main report (Table 2.2-2). Once again, except for the two Manhattan STOLports, daily operations levels should not lead to serious congestion — the peak hour operations rates calculated as before are all less than 35 per hour. The Manhattan STOLports, however, jointly handle between 50 and 80 operations during peak hours and may present some difficulties, depending on the adequacy of the STOLport design and the operational procedures employed.

In summary, the data presented in the Northeast Corridor Transportation Project and de Havilland analyses give an indication of the potential characteristics of intercity STOL traffic, traffic levels, vehicle types, and traffic mix. Potential congestion problems are indicated at a few high-density, city-center STOLports (e.g., New York), at heavily-used general-aviation airfields (e.g., Teterboro or Hanscom Field), and possibly at air carrier airports, if these are used for STOL air service.

ATC System Description

This section discusses the current ATC system and its expected evolution. STOL operations within the ATC system are discussed in the ATC System Interface section.

The design of suitable avionics and flight control systems for STOL vehicles requires, in part, a description of STOL air traffic control procedures — the more detailed the better. However, it is unlikely that STOL procedures will be finalized until some form of STOL service is actually introduced, given the invigorating nature

of practical operating experience. In the interim, projections must be based on current procedures, the expected evolution of the ATC system, and any special STOL operating requirements that can be identified.

The point of view taken herein is that STOL operations should be designed to interface with the expected evolution of the ATC system. STOL air traffic control should, whenever possible, be based on the same general principles and procedures as CTOL air traffic control. This point of view is taken because of the need to minimize STOL system development costs and disruptive impact.

The objectives of an air traffic control system are to provide a safe, expeditious flow of air traffic at a minimum system operating cost. It is helpful to visualize the ATC process in terms of the interacting feedback control loops involved. When such a view is taken, it is apparent that while advanced airborne equipment may be useful in tightening the aircraft control loops, it will not necessarily improve the current ATC system in either capacity or safety.

The air traffic control process is implemented in the current system by means of regulations, procedures, and various active control facilities. Two facilities of central importance are the Air Route Traffic Control Centers (ARTCC's) for en route control, and the Terminal Radar Approach Control Facilities (TRACON's) for approach/departure control.

The ATC system is currently in the process of transition to the so-called Third Generation System. For the Third Generation System the FAA is implementing (1) limited automation to assist the controller, and (2) automated data acquisition through the Air Traffic Control Radar Beacon System (ATCRBS). The automation for the ARTCC's is the National Airspace System (NAS) Stage A program. At the top 64 terminal facilities, the Advanced Radar Terminal System (ARTS III) program is being implemented. NAS and ARTS automation is expected to increase the capacity of the control sectors by 20%.

The future of the ATC system is the subject of a recent report prepared by the Department of Transportation's Air Traffic Control Advisory Committee.⁴ The Advisory Committee's recommendations are aimed primarily at upgrading the Third Generation ATC System to allow it to handle increased traffic levels. Most of their recommendations for upgrading the Third Generation System have been embodied in the FAA's research and development plans for the 1970's.

If the planned automation proves successful and the current schedule is maintained, some of the earliest STOL operations — within a few years after initiation of the service — might be expected to take place within the context of the automated metering and spacing system⁵ currently undergoing development, at least in the busier terminal control areas.

Inasmuch as plans for upgrading the Third Generation ATC System call for encouraging the development of airborne area navigation capabilities, it is reasonable to ask whether or how these capabilities might be used by an automated ATC system of the future. Area navigation systems having time-of-arrival control capabilities (4-D RNAV) are being considered for both V/STOL and CTOL ATC applications. Are such systems compatible with the automated metering and spacing concepts mentioned above? Would such an airborne capability benefit the currently-planned ATC system automation? The answers are almost certainly "yes", but these questions have not as yet been adequately considered.

OPERATIONAL PROCEDURES

This part of the report examines a number of operational aspects of STOL transportation systems which relate to avionics requirements. The areas of interest are (1) flight paths for noise abatement, (2) the atmospheric environment, (3) approach and landing considerations, and (4) the ATC system interface. The analysis in each area is preliminary and should be carried further prior to the required flight test and demonstration programs.

STOL Noise Impact

This section examines the noise impact of STOL operations. The basic noise footprints are examined, as well as noise-abatement procedures. The noise measures used are Perceived Noise Level (PNL), Effective Perceived Noise Level (EPNL), and Noise Exposure Forecast (NEF).

The 95- and 85-PNdB contours of two representative vehicles have been examined. These vehicles, designated PNL95 and PNL100, have basic noise levels of 95 PNdB and 100 PNdB at 500 feet respectively. These basic noise levels are assumed to be measured at takeoff thrust levels. The thrust level on approach was assumed to be half of the takeoff thrust level. The noise generation model is spherical, with no correction for near-ground attenuation or vehicle acceleration. With this model, halving the thrust produces a somewhat greater reduction in PNL than doubling the distance from the source (when within about 1,000 feet of the aircraft).

The noise footprints for these vehicles are small compared with those of current jet transports. A STOL vehicle with a basic noise level of 95 PNdB at 500 feet would produce a 95-PNdB contour that contains less than 1.5% of the area of the corresponding footprint for one of today's 4-engine jet transports.

Some interesting relationships can be observed from the vehicle noise footprints. First, for either the PNL95 or PNL100 vehicles the distance along the runway centerline to a given contour is about 50% greater with a 10-deg climbout than with a 15-deg climbout. This same ratio holds for the area enclosed by the contour. Second, the distance along the runway centerline to the 95-PNdB contour for the PNL100 vehicle is about 50% greater than for the PNL95 vehicle, while the enclosed area is about 2.4 times as great. Third, if one had to make a choice between a PNL100-type vehicle that could climbout at 15 deg, and a PNL95-type vehicle that could only climbout at 10 deg, it appears that for noise reasons the

PNL95 vehicle might be more acceptable, as its centerline distance to the 95-PNdB contour is about the same as for the PNL100 vehicle, but the sideline distance, and hence the area, is about 37% smaller. Of course the importance of this reduction depends on the site and the STOLport configuration. In some cases it may be more important to reduce the distance along the runway centerline than the sideline distance.

The vehicle noise footprints allow one to estimate the length of ground track or area along the runway centerline that would lie within a given PNL contour. For the PNL95 vehicle, assuming a 1,000-foot takeoff roll, a 15-deg climb at full power, and a -7.5-deg approach at half power, the total 95-PNdB contour extends about 5,000 feet along the runway centerline.

For an example relating PNL to NEF, * assume a flight frequency of 100 flights per day. For the PNL95 vehicle, the total NEF 30 contour would then extend about 2,700 feet along the runway centerline (assuming a 15-deg, 80-knot climbout, and a -7.5-deg, 60-knot approach). The contour would not even extend beyond the runway surface on takeoff. In comparison, the NEF 30 contour for the PNL100 vehicle requires about 75% more centerline distance (4,700 feet), and more than three times the area.

Noise-Abatement Procedures

Even though the noise footprints for standard STOL approaches and departures are very much smaller than those for CTOL, it is still useful to look at possible operational procedures for noise reduction.

One procedure which is considered in the main report is a reduced-thrust takeoff. It was assumed that about one-half the normal takeoff thrust could produce a flight path angle about one-third as large as the full-thrust value. † It was found that the area enclosed by the reduced-thrust 95-PNdB contour is less than the corresponding area for full thrust, but that the distance along the runway centerline to the contour boundary is almost 50% greater.

* In calculating EPNL, on which the NEF measure is based, only the duration correction was used; no correction was made for pure tones.

† This approximate relationship was obtained from the performance envelope of the MDC-188 (Ref. 6).

For this kind of takeoff, safety considerations relative to an engine-out failure, such as reduced climb gradient and/or altitude transient, may outweigh the noise considerations. Rather than utilize a reduced-thrust takeoff, it is more likely that a thrust reduction might be employed after some safe altitude had been reached. An analysis was carried out to show how such a two-segment flight path might be chosen.

Using this two-segment procedure, the vehicle approaches the listener until the specified maximum PNL is reached; a thrust cutback is then performed, and the vehicle continues to climb at a reduced flight path angle. The PNL, which decreases when the thrust is reduced, increases again and reaches the specified maximum level as the vehicle passes over the listener. The PNL then decreases as the vehicle continues its reduced-thrust climb.

The thrust-cutback technique trades off vehicle proximity (because of the reduced climb angle) for reduced noise at the source. The results are not always advantageous for the listener. For example, if the thrust cutback point is selected to reduce the 95-PNdB contour for the PNL95 vehicle, a 36% reduction in the extent of the contour is achieved. However, while the 95-PNdB contour is reduced, the 85-PNdB contour is lengthened by over 1,000 feet because the climb angle is reduced after the thrust cutback. If the thrust cutback is timed to reduce the 85-PNdB contour, a 32% decrement is achieved. In this case the 95-PNdB contour is not affected. Similar results are obtained for the PNL100 vehicle.

On the basis of this analysis, it appears that if there is a small, particularly sensitive area close-in to the STOLport, such as a group of houses, a school, a hospital, or a concert hall, a thrust cutback can provide some reduction in annoyance. However, for most listeners the reduction would be barely perceptible (3-5 PNdB). As the basic vehicle noise decreases, the thrust cutback becomes less meaningful, as smaller areas can share in the PNL reduction.

On landing approach, noise reduction procedures may be limited due to piloting constraints — such as (1) a reluctance to exceed a rate of descent greater than about 1,000 ft/min close to the ground, and (2) a desire to be aligned with the runway and on the final-approach slope when breaking out of the clouds at 200 feet in Category I weather conditions. The respective times between breakout and touchdown for approach slopes of -7 and -9 deg are about 15 and 12.5 sec respectively for an approach speed of 60 knots. This compares with about 20 sec for a CTOL aircraft on a 120-knot, -3-deg approach. The acceptability of reducing the final-approach segment would depend on the performance and reliability of the avionics systems,

and perhaps the crosswind component and/or turbulence level. An analysis of the type discussed in the Approach and Landing Considerations section, extended to include vehicle dynamics, wind effects, and pilot performance, would be very useful in helping to determine approach profiles. It is apparent that if NEF 30 is the guideline for noise acceptability, then approach maneuvering will probably not lead to very significant NEF changes for a PNL95-type vehicle, simply because the NEF 30 contour is quite small.

Flight Path Optimization

Supplementing the above STOL noise studies, a steepest-descent optimization program was used to generate takeoff flight paths that minimize the annoyance perceived by a number of listeners along the flight track. The program models the flight of an augmentor-wing jet STOL vehicle on a two-dimensional flight path. The state variables are velocity, flight path angle, altitude, and downrange; the control variables are pitch angle, primary thrust, augmentor thrust, and the primary thrust incidence angle. In addition, several cases include the flap angle as a fifth control variable. The problem includes inequality constraints on both state and control variables.

The results indicate that in general the vehicle should climb to altitude using full thrust and maximum flight path angle. Over sensitive areas, however, thrust cutbacks can reduce the maximum PNL, although such a maneuver increases the peak PNL for the downrange listeners. The thrust cutbacks in this study were extreme, due to the modeling of listeners as discrete points. In a real situation more moderate cutbacks would be employed.

The program was run a number of times to include variations in initial conditions, vehicle thrust-to-weight ratio, and listener location. These variations did not alter the general conclusion that STOL departures should utilize full thrust and maximum flight path angle in order to minimize the total annoyance of all listeners. Further studies should examine the economic and noise tradeoffs involved in providing STOL with higher thrust for increased climb angle capability.

Wind Conditions Affecting Landing

The atmospheric environment is discussed because of its expected impact on STOL avionics requirements, particularly in the areas of crosswind landing capability and gust alleviation. Three types of wind conditions are considered: (1) mean wind,

which is the velocity of the air relative to the ground at some reference altitude; (2) boundary layer shear, which is the vertical variation of the horizontal wind velocity; and (3) turbulence, which is a random variation of wind velocities from the steady-state (mean wind and boundary layer shear) velocities. Methods for modeling low-altitude turbulence are discussed.

Information is available at many airfields concerning mean winds experienced over the past few decades, and these records provide a firm base for statistical analyses of future wind conditions. These records are published in various forms by U.S. government agencies and generally provide such information as percentage occurrences of wind speeds and directions, visibilities and ceilings, and useful correlations of these occurrences.

The probabilities of exceedence of critical crosswind velocities in particular are very important to the STOL aircraft operator. Data for surface winds at South Weymouth Naval Air Station,⁷ one of the possible STOLport locations in the Boston area, has shown that the probabilities of crosswinds to given runway orientations can be approximated as normal distributions, although noticeable deviations do occur, particularly at the higher velocities. Actual data should be used for accurate predictions of the percentage of incompleting flights due to crosswinds.

The wind shear (vertical gradient of horizontal velocity) in the boundary layer near the ground may affect an aircraft during final approach. The thickness of the boundary layer, and hence the shear experienced by the aircraft, depends on the conditions of the flow — and especially the turbulence in this layer. In order to predict shear, investigators have attempted to associate it with surface roughness or thermal atmospheric conditions, which are representative of the amount of turbulence to be expected.

Turbulence is characterized by its random, and hence generally unpredictable, nature. It can therefore only be described in terms of expectations — that is, by the statistics. In this regard, a very useful measure of the turbulence is the power spectral density (PSD) of the turbulence velocities.

At low altitudes, the von Karman or Dryden spectrum (applicable to turbulence at altitude) can be scaled by the rms turbulence velocities ($\sigma_u, \sigma_v, \sigma_w$), the frictional velocity u^* , and the scale lengths in the various directions. Moreover, whenever the air near the ground is thermally unstable, it will be necessary to include a convective turbulence peak in the low-altitude model of the power spectral density. The convective peak should be added at a wavelength about 10 times the characteristic

length of the unmodified spectrum, and should have a peak of up to 10 times the value of the flat portion of the spectrum.

In order to consider the effect of turbulence onboard the aircraft, the spatial model statistics must be reformulated in the time domain of the moving aircraft. The aircraft is pictured as moving through a field of turbulence which is frozen except that it translates with the mean wind (Taylor's hypothesis). A power spectral density can then be written in the time domain rather than the space domain.

There are various types of turbulence which do not follow the above behavior. These include clear air turbulence, turbulence induced by buildings and terrain features, aircraft-wake turbulence, and turbulence associated with storms.

More extensive information about turbulence would assist in improving turbulence models. Two types of studies would be particularly helpful: (1) statistical studies of turbulence measurements near airfields; and (2) further theoretical work and measurements designed to assist in the understanding of the basic physics of turbulence.

Approach and Landing Considerations

This section describes a simple method of examining the approach and landing constraints for an aircraft nearing an MLS-equipped runway.

The approach and landing phase is modeled as follows: a straight line base leg (at some angle to the runway centerline), followed by a constant radius turn to bring the aircraft onto the extended runway centerline for final approach. The turn is assumed to begin when the localizer beam is intercepted, such that the circular path is performed within the localizer coverage. The flight path angle is assumed constant.

The linear dimensions of the problem can be conveniently normalized with respect to the aircraft turning radius R ; thus the approach is defined by the intercept angle and the normalized final-approach distance (d/R), where d is measured from the touchdown point.

Plots are derived which show the allowable intercept angles as a function of the normalized final approach distance for various localizer and glide slope coverage angles.

These plots can be used in two ways: to determine the allowable approach paths to a given ILS configuration, or to specify ILS coverage to accommodate desired approach paths. The curves indicate that for a highly maneuverable STOL vehicle, with R varying between 500 and 1,000 feet, a wide range of approaches can be made with relatively modest localizer and elevation coverage.

The analysis presented here utilizes a number of simplifying assumptions, such as no pilot or vehicle response lags. These factors should be incorporated into the analysis, as well as such effects as headwinds and crosswinds, and pilot requirements for minimum time on final, etc.

ATC System Interface

STOL operations within the context of the existing and evolving ATC system are the subject of this section. Operational procedures and problems are discussed, with emphasis on avionics and ground-system requirements.

Runway Capacity

The STOL demand levels hypothesized indicate that providing adequate runway capacity may be a problem in certain of the larger demand centers. In order to determine whether or not this is the case it is necessary to know the capacity of a runway or a set of runways used for STOL operations. It is also necessary to know how capacity is affected by separation standards, regulations, and operational procedures, since these may be subject to change.

There are two basic ATC safety requirements which impact the minimum landing interval for a single runway. The first is the requirement that the runway be clear of the preceding arrival (or departure) before the landing aircraft crosses the runway threshold and is committed to land. The second is the requirement that IFR aircraft be separated by some minimum distance S , which is currently 3 n.mi. if radar separation procedures are in use and the aircraft are within 40 n.mi. of the radar installation.

For STOL aircraft using current IFR procedures, only the second requirement would affect the minimum landing interval, because runway occupancy times are short (on the order of 15 sec if adequate exits are provided), and approach speeds are slow. The minimum landing interval with a 3-n.mi. separation requirement and a 60-knot approach speed is 3 min. Reduced separation requirements may of

course be adopted for STOL operations, but unless the time separation in the air approaches the runway occupancy time (which seems unlikely from the safety point of view), the general conclusion remains the same: the bottleneck is not the runway but instead, the approach airspace. From the reaction-time point of view, separation could certainly be reduced. A 1.5-n.mi. separation with a 60-knot approach speed results in a 90-sec time separation, more than adequate for controller/pilot communication and reaction.

The effect on maximum arrival rate of mixing STOL and CTOL aircraft is examined in the main report for various values of final common path length. Even a small percentage of STOL traffic in the arrival stream greatly reduces the arrival rate. This is caused mainly by the low STOL-only arrival rate, but a further degradation occurs as the length of the final common path is increased.

A runway can be regarded as a service facility. It can be used by only one aircraft at a time (arrival or departure), and other aircraft seeking to use it must be delayed until it is free. When the runway occupancy time for arrivals is very small, the separation requirements in the approach airspace limit the minimum landing intervals, as we have observed. In this case, arriving aircraft must queue for the use of the approach airspace as well as the runway, and the approach airspace can also be regarded as a service facility.

When a runway is used for both arrivals and departures, the situation becomes considerably more complicated. Departure aircraft form a second queue for runway usage, and the characteristics of this queue must be examined. Present ATC procedures give landing aircraft priority over departures for use of the runway, a practice which can lead to long departure queues and delays. Long departure queues could not be accommodated at a small STOLport, making the investigation of the arrival/departure process particularly pertinent.

To calculate the Practical Hourly Capacity (PHOCAP) of the runway used for mixed operations, it is necessary to know both the arrival capacity and the departure capacity. If the arrival/departure ratio is unity, then the Practical Hourly Capacity is defined to be twice that of the lower capacity of the two streams of traffic. In the normal case when the departure capacity is less than the arrival capacity, the runway is said to be "departure-limited". In the STOL situation, the runway tends to be "arrival-limited" because the low STOL approach speed combined with the short STOL runway occupancy time provides ample opportunities for the release of departures.

In order to minimize the cost and disruptive impact of STOL operations within the ATC system, it is desirable to limit specialized procedures and regulations to only those deemed most essential to the success of the venture. From the runway capacity point of view, it would appear that special reduced separation regulations are essential for STOL. The Practical Hourly Capacity under present standards for mixed operations on the STOL runway at a mean arrival delay of 2 min is only 23 operations per hour (half arrivals and half departures). If the required arrival/arrival separation is reduced from 3 n.mi. to 1.5 n.mi. and the arrival/departure separation from 2 n.mi. to 1 n.mi., then the Practical Hourly Capacity becomes 52 operations per hour.

A 2-min mean delay level has arbitrarily been selected as a capacity reference. One of the important areas for future work is to determine acceptable delay levels for STOL. STOL transportation systems are shown to be economically feasible or infeasible on the basis of trip time and costs, both of which increase with increased terminal area delays. Future economic studies should attempt to include the effects of congestion and terminal area delays in their considerations.

Finally, the need for empirical data on STOL runway service times and delays should be emphasized. Real-time ATC simulations can be of use here, as can flight test data on runway occupancy times for arrivals and departures, pilot reaction times, and the like.

STOL Operations at Metropolitan Jetports

Although there are many reasons why one would want to implement an independent STOL transportation system operating without congestion from centrally-located STOLports, the desirability of STOL operations at metropolitan jetports is less clear. Such operations may be found to be necessary in some instances because sites for separate STOLports either cannot be found or are too expensive. Also, the economics of air transportation may dictate that STOL flights connect with existing CTOL flights (both long-haul and short-haul) to satisfy the needs of the air traveling public. Finally, STOL vehicles may be able to utilize runway facilities not usable by conventional aircraft due to noise-abatement restrictions, runway-length limitations, or obstacle-clearance problems, and hence increase airport capacity. The key issue in this case is whether safe, reliable STOL operations can be conducted without interfering with CTOL operations.

There are three main ways of implementing STOL/CTOL operations at jetports. These are STOL/CTOL operations on the same runway, on intersecting runways, and on parallel runways.

Upon considering these types of operations in the light of current and evolving ATC procedures, it is concluded that noninterfering, capacity-enhancing STOL/CTOL operations at jetports should be possible if the STOL and CTOL vehicles use separate runways. Under IFR conditions, the two possibilities for noninterfering landing operations would appear to be (1) simultaneous ILS (or MLS) approaches to parallel runways, and (2) synchronized operations on intersecting runways (to avoid possible conflict at the intersection). In the first instance, parallel STOL runways having sufficient separation (5,000 feet) from the CTOL runways would be needed. Reducing the required separation is an important avionics and ground-system design goal. In the second instance, additional aids to the controller (such as the ARTS III metering and spacing system) would be necessary to increase efficiency and reduce controller workload, and the 3-n.mi. separation rule (for aircraft on separate runways) would have to be amended. In examining the tradeoffs between these two types of operations, particular attention must be paid to taxiing delays caused by remote runway locations and taxiway/runway interference.

Synchronization of operations might be useful for the reduced-separation parallel-runway case as well as the intersecting runway case in order to avoid arrival/departure (or wake turbulence) interference.

A detailed safety analysis of STOL operations at jetports is recommended to aid in establishing separation standards and emergency procedures.

STOLport and Suburban Airport Operations

In this final section, the geographic region of interest is expanded beyond the immediate environs of the jetport to encompass the approach and departure airspace as well as possible non-jetport STOL terminals in the metropolitan area. An examination of the proposed STOL terminal sites reveals that the use of both downtown STOLport facilities and suburban general-aviation airfields is contemplated.

Operational procedures for landing V/STOL aircraft in a congested terminal area environment (Los Angeles) have been investigated in a NAFEC simulation study.⁸ With respect to the approach airspace, the most pertinent test results were these:

1. Establishing proper separation between the V/STOL aircraft prior to transition proved to be a high-workload task.
2. Because of the workload involved in providing separation for the V/STOL aircraft, an additional controller was required to handle arrivals to the City Center Metroport (the V/STOL facility).

3. Separate arrival routes for V/STOL aircraft were found desirable when the V/STOL and CTOL aircraft landed on independent runways, but were of no value when they landed on the same runway.

In 1969, an FAA staff study was prepared entitled: "The Feasibility of Establishing Downtown STOLports in New York City, Los Angeles, and Chicago."⁹ The study concluded that downtown STOLports would be feasible from an air traffic control point of view in each of the three cities, but suggested that a network of suburban STOLports might better serve the transportation needs of the Los Angeles area. Since the study did not involve simulation of traffic control procedures, the feasibility conclusion should be regarded as preliminary.

These studies indicate that STOL operations at separate STOLports and suburban airports within major terminal areas can be accommodated using existing procedures for the most part. One or more satellite positions at the TRACON may be necessary, as well as tower controllers for special STOLport facilities. Avionics and ground-system improvements should concentrate on the following problem areas:

1. Assistance to the controller in establishing pre-transition separation.
2. Methods for standardizing STOL deceleration profiles during transition.
3. Methods for reducing the airspace required for controlling STOL/STOL separation on final approach.
4. Ways to improve the adequacy of navigation aid and radar coverage at certain problematic STOLport sites.
5. Methods for enhancing the safety of STOL operations at suburban airports.
6. Collision avoidance assistance for STOL pilots operating amidst general-aviation traffic in the terminal area.

It is recommended that limited-scale demonstration projects be undertaken using actual STOL vehicles to assist in identifying operational problems and in establishing detailed operating procedures.

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CONCLUSIONS AND RECOMMENDATIONS

The principal conclusions and recommendations which have resulted from this inquiry into the STOL traffic environment and operational procedures are summarized in this section. The reader is referred to the specific sections of the main report for a detailed discussion and for additional conclusions and comments.

TRAFFIC ENVIRONMENT

STOL Traffic Characteristics

1. Several recent system studies have indicated the possibility of an economically successful STOL system in which substantial numbers of vehicles are involved (e.g., 3,000 daily operations in the Northeast Corridor by 1982). (Section 2.2)
2. There would be enough traffic at some STOLports to warrant concern about peak-hour congestion (e.g., 50 to 80 operations in a peak hour for a Manhattan STOLport complex in 1982). (Section 2.2)
3. The projected traffic levels indicate potential capacity problems for STOL operations at heavily-used jetports and general-aviation airports given current ATC system policy and procedures. (Section 2.2)

ATC System Description

1. STOL air traffic control should be based on the same general principles and procedures as CTOL air traffic control in order to minimize development costs and disruptive effects. (Section 2.3)
2. If planned ATC automation programs are implemented as scheduled, STOL operations in the larger terminal areas might be expected to take place within the context of the automated metering and spacing system currently being developed. (Section 2.3)
3. The use of area navigation systems having time-of-arrival control capabilities (4-D RNAV) appears promising for terminal air traffic control and should be investigated further. Expected benefits include reduced controller/pilot

communication, reduced pilot workload through the use of automated systems onboard the aircraft, and reduced airspace requirements to effect the terminal ATC process. (Section 2.3)

OPERATIONAL PROCEDURES

STOL Noise Impact

1. A STOL vehicle with a basic noise level of 95 PNdB at 500 feet would produce noise contours that contain less than 1.5% of the area of the corresponding contours of today's 4-engine jet transports. (Section 3.2.3.1)
2. When both STOL and CTOL are outfitted with quiet engines, STOL should still have significantly smaller noise contours due to shorter ground rolls and steeper flight path angles. Further study is needed to define the noise/cost tradeoffs involved in increasing engine power for steeper flight path capability.
3. Assuming 100 operations per day, the NEF 30 contour for the above-mentioned STOL, if it had a climb capability of 15 deg and an approach slope of -7.5 deg, would extend less than 3,000 feet along the runway centerline. A contour of this size might be completely contained within the STOLport property limits. (Section 3.2.3.1)
4. Thrust cutbacks after takeoff can provide moderate reductions in annoyance (3-5 PNdB) for certain areas under the flight path. In general the quieter the vehicle the smaller the area of noise reduction for a given noise level. (Section 3.2.3.2)
5. In general the least annoying flight path is one of maximum flight path angle when listeners are evenly distributed along the flight path. (Section 3.2.4.4)
6. Three-dimensional flight paths should be examined for their noise-reduction potential over certain areas, especially in conjunction with thrust cutbacks. Particular parameters to be defined are minimum IFR/VFR final-approach distances, and maximum allowable bank angle as a function of altitude.

Wind Conditions Affecting Landing

1. U.S. government data on winds and ceiling/visibility correlations at a typical airport show that STOL aircraft will require a crosswind landing capability of at least 20 mph if they are to have a trip completion ratio of 99.5% or better (assuming adequate landing capability in poor ceiling/visibility

conditions). Since some single-runway sites may have unfavorable runway orientation or higher wind probabilities, STOL crosswind capability may have to be as high as 30-35 mph. (Section 3.3.1)

2. Except for storms, low visibility conditions tend to be accompanied by low winds and low turbulence. (Section 3.3.1)
3. The probabilities of runway crosswind velocities can be modeled as Gaussian distributions, but actual data is necessary for accurate prediction of the percentages of incompleting flights due to crosswinds. (Section 3.3.1)
4. Turbulence within about 1,000 feet of the ground can be modeled by considering the three coordinate directions separately and by adding to the standard von Karman or Dryden power spectral densities a low-frequency convective peak centered at about one-tenth the characteristic frequency and having a peak amplitude of up to 10 times the amplitude of the flat portion of the spectrum. Although such a PSD peak would usually occur only on sunny VFR days, analysis of STOL approaches is needed to determine the effect of this low-frequency turbulence on glide slope following and touchdown accuracy. (Section 3.3.5.2)
5. Analysis is required in several areas relating to wind effects, notably the effects of wake turbulence on longitudinal and lateral separation, and the effects of wind shear on piloted and automatic landings.

Approach and Landing Considerations

1. A simple model of the MLS approach and landing interface indicates that a wide range of approach flight paths for STOL aircraft is possible with modest landing-aid coverage (localizer and glide slope). This model should be extended to include such realistic constraints as headwinds and crosswinds, pilot and vehicle lags, and ground and airborne equipment uncertainties. (Section 3.4.2)

ATC System Interface

1. It is recommended that special reduced-separation requirements be adopted for STOL operations in order to assure adequate runway capacity. Reducing the IFR arrival/arrival separation from 3 n.mi. to 1.5 n.mi. and the arrival/departure separation from 2 n.mi. to 1 n.mi. can more than double the Practical Hourly Capacity of a STOLport. (Section 3.5.1)
2. Noninterfering, capacity-enhancing STOL/CTOL operations at jetports under IFR conditions should be possible using simultaneous ILS (or MLS) approaches

to parallel runways, or (2) synchronized approaches to intersecting runways. It is recommended that avionics and ground-system requirements for implementing these procedures be investigated. (Section 3.5.2)

3. If STOL vehicles are to operate safely and efficiently in congested terminal airspace, avionics and ground-system improvements are needed in several areas (e.g., control of in-trail separation through the transition maneuver, and collision-avoidance assistance for operations at suburban airports). (Section 3.5.3)

DEFINITION OF STOL OPERATING ENVIRONMENT

This section provides an estimate of the STOL operating environment over the 1975-1990 time period. This estimate, which is based on development plans, study projections, and engineering judgement, is aimed at aiding STOL flight test program planning. It is subject to the normal limits on prognostication, compounded by the present political and economic uncertainties relating to financing, operating, and regulating a STOL service.

The operating environment is divided into two time frames, Phases I and II, with the breakpoint separating the two periods in the 1985-1990 period. Phase I represents the evolution of ground and airborne systems along lines already established, with automation being employed mainly to improve safety and reduce controller/pilot communication and workload. Phase II starts with the advent of airborne 4-D RNAV capability, which allows a sharing of the system control functions between ground and onboard systems, and has the potential of providing significant increases in airspace and runway capacity.

The items below outline our estimate of the Phase I operating environment. A discussion of Phase II follows the Phase I description.

Phase I Environment

TRAFFIC ENVIRONMENT

STOL Traffic Characteristics

1. It is assumed that an economically successful intercity STOL system involving a substantial number of vehicles will be implemented in the 1975-1990 time period (e.g., 3,000 daily operations in the Northeast Corridor by 1982). (Section 2.2)
2. STOL operations will take place at STOLports, jetports, and suburban airfields. (Section 2.2; Appendix A)
3. The STOL fleet will evolve into a mixture of large jet-STOL vehicles and small and medium-sized propeller-driven STOL vehicles. (Section 2.2)
4. There will be enough traffic at some STOLports to warrant concern about peak-hour congestion (e.g., 50 to 80 operations in a peak hour for a Manhattan STOLport complex in 1982). (Section 2.2)

5. The traffic levels projected for STOL operations at heavily-used jetports and general-aviation airports will necessitate the development and application of noninterfering STOL/CTOL operating procedures. (Section 2.2)

ATC System Description

1. STOL air traffic control will be based on the same general principles and procedures as CTOL air traffic control in order to minimize development costs and disruptive effects. (Section 2.3)
2. In the larger terminal areas, STOL operations will take place within the context of the automated metering and spacing system currently being developed. (Section 2.3.3)
3. An automatic, digital data link will be in use for both routine and time-critical ATC commands. (Section 2.3.3)
4. Collision avoidance or proximity warning systems (possibly intermittent positive control) will be used to enhance the safety of STOL operations amidst general-aviation traffic in the terminal area and at suburban airfields. (Section 3.5.3)
5. Additional controllers and tower personnel will be required to handle operations at separate STOLports within the terminal area. (Section 3.5.3)

OPERATIONAL PROCEDURES

STOL Noise Impact

1. It is assumed that STOL vehicles operating in the 1975-1990 time period will have basic noise levels of 95 PNdB or less at 500 feet. (Appendix B)
2. In general STOL climbouts will be at maximum flight path angle, as this minimizes the total annoyance when listeners are evenly distributed along the flight path. (Section 3.2.4.4)
3. Thrust cutbacks after takeoff, which result in moderate noise reductions (3-5 PNdB) over certain areas, will be required at some sensitive STOLport sites. Such maneuvers will probably not be required at most sites however, due to the low basic noise level of these aircraft. (Section 3.2.3.2)
4. Curved flight paths will be used frequently for STOL operations in order to avoid noise sensitive areas. Analysis is needed to define the effect of such maneuvering on PNL and NEF contours. Particular parameters to be defined include minimum IFR/VFR final-approach distances, and maximum allowable bank angle as a function of altitude.

Wind Conditions Affecting Landing

1. It is assumed that STOL aircraft will have the capability to land with crosswind components of at least 20 mph (probably as high as 30-35 mph). This should allow trip completion ratios of 99.5% or better (assuming adequate landing capability for poor ceiling/visibility conditions) at STOLport and jetport sites where STOL runways may not be aligned favorably with respect to the prevailing winds. (Section 3.3.1)

Approach and Landing Considerations

1. It is assumed that the terminal landing aids will have sufficient coverage and accuracy to permit curved approaches down to the runway threshold. This coverage will allow approaches of at least 90 deg to the runway centerline, followed by a constant-radius turn down to the threshold. Further work is needed to determine the limits on approach angles and turn radii, and to determine touchdown accuracy for automatic and piloted landing. (Section 3.4.2)

ATC System Interface

1. It is postulated that IFR arrival/arrival separation for STOL will be reduced from 3 n.mi. to 1.5 n.mi. or less, and that the arrival/departure separation will be reduced from 2 n.mi. to 1 n.mi. or less in order to provide adequate runway capacity. A safety analysis is needed in order to verify the practicality of these reductions. (Section 3.5.1)
2. Wherever possible, STOL and CTOL operations at jetports will be kept separate; noninterfering, capacity-enhancing STOL/CTOL operations will be conducted under IFR conditions using (1) simultaneous ILS (or MLS) approaches to parallel runways, or (2) synchronized approaches to intersecting runways. Avionics and ground-system requirements for implementing these procedures must be investigated. (Section 3.5.1; 3.5.2)
3. Separate STOL arrival routes between feeder fixes and STOL runways will be used in the terminal area whenever sufficient airspace is available. (Section 3.5.3)

Phase II Environment

One of the tasks of this project was to define two STOL operating periods, the second to have more advanced equipment and operating procedures than the first. Because of the expected evolutionary growth of a STOL system, the selection

of a breakpoint is somewhat problematic. However, there is a possible development in the ATC environment that significantly impacts the equipment and procedures associated with both ground and airborne control systems; that development is the introduction of airborne four-dimensional area navigation (4-D RNAV) into the ATC system, which could occur in the 1985-1990 time period.

The major impact of airborne 4-D RNAV will probably be to reduce communication and separation requirements, which will increase airspace utilization and runway capacity. This results from a control strategy in which the ground determines a 4-D flight path (position/time) for each aircraft and sends this information to the aircraft via data link. The aircraft then becomes responsible for maintaining the flight path with great precision using its onboard control, guidance, and navigation equipment.

It should be pointed out that the automated metering and spacing feature of the ARTS III terminal area ATC system (see Section 2.3.3) will provide a 4-D RNAV capability as early as 1975, but this capability is expected to provide only small increases in runway and airspace capacity due to the slow ground-based control loop and the relatively inaccurate navigation aids available. It is only when a fast control loop and accurate navigation aids can be employed together that airport/STOL-port capacity can be increased significantly.

A necessary component of a 4-D RNAV system is accurate navigation information, since position following is only as good as position information. It is assumed that by 1985-1990, aircraft navigation aids will provide position information accurate to within tens of feet. Whether or not the navigation system will be satellite-based is indeterminate now, but it appears that a satellite system of sufficient accuracy could be in service by that time.

The use of airborne 4-D RNAV appears particularly advantageous for the control of STOL aircraft in the terminal area. Simulation studies (see Section 3.5.3) have shown that maintaining accurate time-of-arrival and separation control through the STOL transition maneuver using ground-based traffic control procedures is difficult and may forestall the use of reduced longitudinal separation on final approach. Reduced separation is needed to provide adequate STOL runway capacity (see Section 3.5.1). Airborne 4-D RNAV systems should be capable of providing the improved time-of-arrival control needed during the transition maneuver.

The possible evolution of the 4-D RNAV system is outlined in Figure ENV-1. Shown here are the key features of the ATC and airborne systems arranged in an estimated timeline. Also shown are the operational procedures corresponding to the ground/airborne systems' state of development.

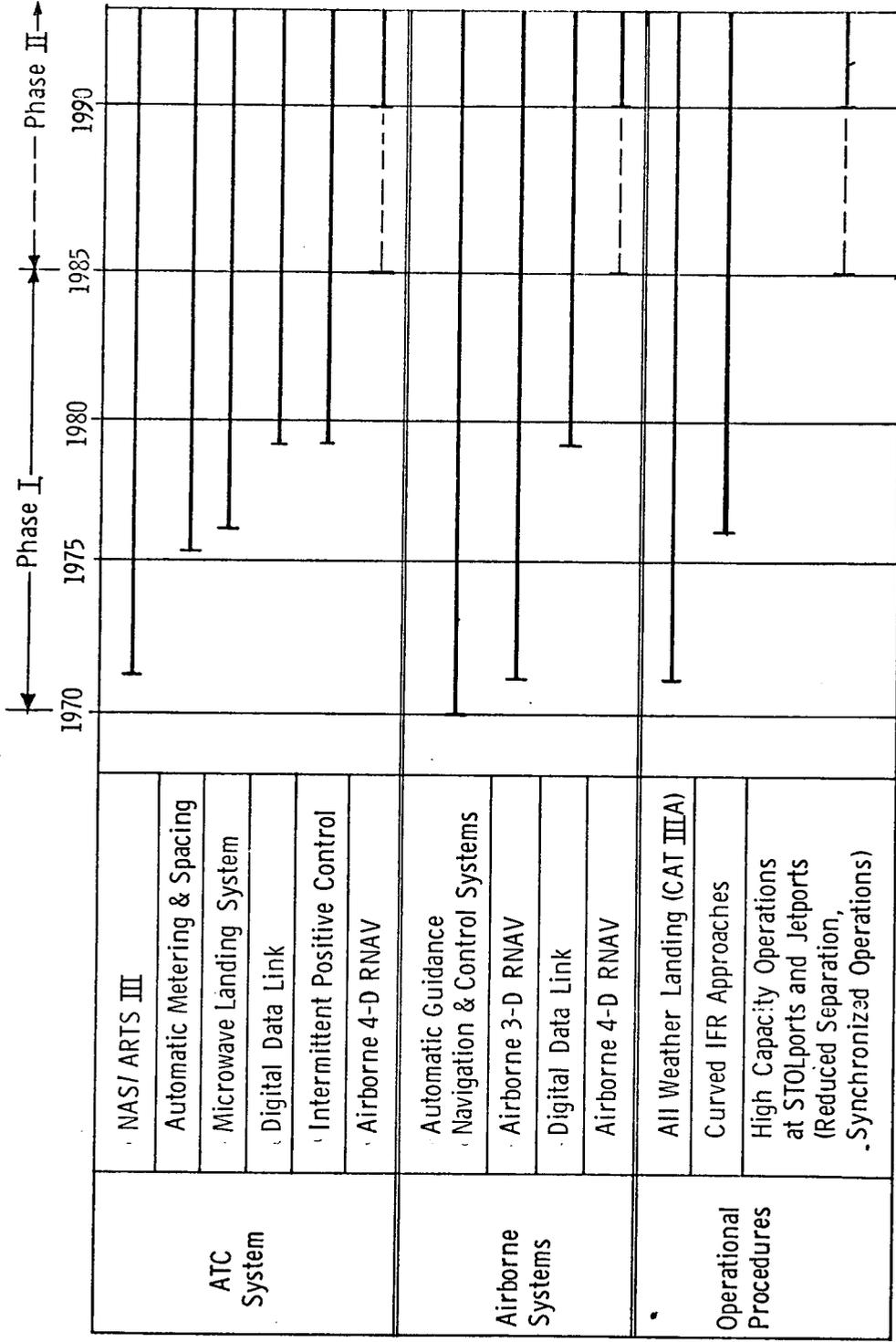


Fig. ENV - 1 Possible Evolution of the STOL Operating Environment

With the exception of the 4-D RNAV capability, the ATC developments are taken from the FAA ten-year plan for the 1973-1982 period. The advent of 4-D RNAV in the 1985-1990 period represents a departure from the established ATC policy of tactical ground-based control, in that the ground will compute flight paths strategically and the aircraft will be responsible for maintaining the flight paths; thus the control responsibility will be shared between airborne and ground systems.

The airborne systems will probably undergo continuous development over the years, providing capabilities for autoland, curved approaches in conjunction with the MLS and datalink, and, with the addition of velocity control for all flight regimes, precise 4-D RNAV all the way to touchdown for high-capacity terminal area operations.

Significant problems associated with the introduction of airborne 4-D RNAV systems include (1) the possible need to mix RNAV-equipped and non-RNAV-equipped aircraft in the same airspace, at least during some transitional time period, and (2) the design of cooperative control algorithms that will allow ground monitoring of airborne system performance. It is assumed that the benefits to be accrued due to tighter airborne control of terminal area flight-paths will motivate the solving of these problems and lead in time to adoption of 4-D RNAV procedures for controlling at least a portion of the air carrier traffic in the terminal area.

CHAPTER 1

INTRODUCTION

Prior to the introduction of a new STOL short-haul transportation service, it is necessary to identify and understand the expected operational environment. Such understanding will aid in establishing STOL avionics requirements. This report examines two aspects of the STOL operating environment. The first, which is called the Traffic Environment, encompasses such factors as STOL demand, the size and mix of vehicles (STOL, CTOL, and VTOL), STOLport location, runway and terminal area capacity, and the air traffic control (ATC) system. The second, entitled Operational Procedures, addresses noise impact, flight path definition, atmospheric effects, and interaction with the final-approach landing aids. Consideration is also given to the ATC problems associated with STOL operations at jetports, suburban airports, and separate STOLports.

The air traffic environment is covered in Chapter 2. The discussions on STOL demand, traffic mix, and STOLport locations are based on interpretations of previous studies. The ATC system is examined in its present state, and the planned evolution of the equipment and procedures is described.

STOL operational procedures are dealt with in Chapter 3. Again, existing studies are reviewed for their application to STOL operations. The noise section discusses two methods of defining noise-abating flight paths. The atmospheric section provides an examination of low-altitude atmospheric turbulence, as well as discussion and examples relating to ceiling/visibility and runway crosswind data. The landing approach section presents a method for determining limits on final approach flight paths as a function of the landing aid geometry. The ATC interface section discusses STOL operating procedures at jetports, STOLports, and suburban airports, as well as STOL runway capacity. The STOL runway capacity analysis is an appropriate modification of the analysis used for CTOL operations.

It is the intent of the report to provide a better understanding of the potential STOL operating environment, and to suggest possible solutions to some problem areas. An attempt has been made to identify those problem areas which impact on avionics and ground-system requirements. There remain, however, several critical areas requiring significant additional work prior to the introduction of commercial STOL service. These are discussed in the conclusions and recommendations of the separate sections.

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CHAPTER 2

TRAFFIC ENVIRONMENT

2.1 INTRODUCTION

The intent of this chapter is to examine the expected traffic environment for an intercity STOL transportation system in order to facilitate the definition of STOL operating procedures. This in turn should aid in establishing STOL avionics requirements.

A description of the expected STOL air traffic environment for planning purposes should consider two aspects of STOL air traffic: the characteristics of the traffic — that is, the traffic densities, vehicular types, and the traffic mix expected in various geographical regions at future times — and the control of the traffic in terms of air traffic control procedures and policies. The expected traffic characteristics will be discussed in Section 2.2, and the traffic control in Section 2.3.

Traffic characteristics as portrayed in a number of recent system analyses are examined in Section 2.2 in order to identify possible STOL/CTOL or STOL/STOL interaction problems. Some of the expected traffic levels are sufficient to cause congestion problems at the busiest of the proposed STOLports. STOL/CTOL traffic-conflict problems are indicated for STOL operations at jetports and general aviation airports unless noninterfering operational procedures can be developed.

The current state and expected evolution of the air traffic control system is reviewed in Section 2.3. For the purpose of developing operational procedures, the ATC system has been taken as "given" in order to minimize development costs and disruptive impact. Plans for the development of automated terminal ATC procedures are reviewed in some detail.

2.2 TRAFFIC CHARACTERISTICS

In the past six years a large number of studies have been devoted to the technical and economic analysis of STOL (and VTOL) short-haul air transportation systems.* Most of these studies have dealt with the interurban travel market having stage lengths of less than 500 miles. Some have considered intraurban applications, while a few have dealt with regional, recreational, or other types of air services.

Conclusions regarding the economic viability of STOL air systems have varied. Generally speaking, the economic viability conclusion hinges on assumptions made regarding transportation demand and modal preferences, vehicle and service characteristics, terminal locations, operating costs, and the allocation of costs among the operator, the federal government, and the affected municipalities. In any case, economic viability (and technical feasibility) has not been demonstrated to the extent necessary to attract the investment capital.

In the absence of a clear plan or commitment on the part of an air carrier or appropriate government body to implement a STOL air transportation system in any of the potential interurban domestic markets (the only type of STOL service to be considered here), it is not possible to be very certain about future traffic characteristics. An interurban STOL air service may never materialize. However, a number of the above-cited economic and system studies have depicted a successful STOL air service in which substantial numbers of vehicles are involved. Since the presence of a large number of STOL vehicles in short-haul air service may pose problems for the air traffic control system, certain of these studies will be considered in more detail.

In particular, the interurban traffic characteristics as depicted for the Northeast Corridor by two of the above studies will be considered. These are the Northeast Corridor Transportation Project Report² and supporting volumes, and the Civil Aeronautics Board's Northeast Corridor VTOL Investigation,³ specifically the exhibits prepared by de Havilland Aircraft of Canada, Ltd.⁴

A few words are in order about some of the Northeast Corridor's[†] prospects and problems as they relate to transportation needs. The prospects include continued population growth coupled with an increasing disposition to travel, and continued population migrations. The increasing disposition to travel is reflected by the fact

* An extensive annotated bibliography will be found in Ref. 1.

† The term Northeast Corridor as used herein refers to the urbanized northeast seaboard of the United States from about 50 miles north of Boston, Massachusetts, to the southern border of Virginia.

that demand for intercity transportation is growing at more than twice the population growth rate (4% per annum as opposed to 1.8% per annum).² The major population migrations, from rural to urban areas and from city centers to suburbs, are expected to continue, leading to still more sparsely settled rural areas and sprawling urban concentrations.

Most of the transportation problems in the Corridor are related to these population growth and distribution trends. It is difficult to provide common carrier transportation to rural and suburban areas without subsidy. This difficulty has led to increasing rural isolation and a dependence in the suburbs on the private automobile as an intercity mode. Access from suburban areas to airports and city-center ground transportation terminals has become very difficult as a result of urban congestion. Demand has been outpacing capacity (at least at peak hours) in both the highway and air modes as evidenced by highway congestion in the vicinity of urban areas and by congestion on the ground and in the air surrounding airports. Traditional solutions, the construction of new highways and new airport facilities, are no longer as feasible as they once were, due not only to environmental pollution considerations, but also to severe space limitations within the urban portions of the Corridor. The land requirements for both expressway and airport construction are substantial. For example, a new airport for large, conventional air vehicles requires from 5,000 to 10,000 acres of land with compatible surroundings. For this and other reasons, new ways of providing for the area's future intercity transportation needs seem to be required.

The Northeast Corridor Transportation Project was established as a formal project within the Department of Commerce in 1964; it was later transferred to the Department of Transportation. It had as its goal the determination by systems analysis techniques of intercity transportation facility requirements for the Northeast Corridor through 1980. A project status report, consisting of eighteen volumes, was forwarded to Congress on May 4, 1970. The summary volume describes a cost/benefit analysis of nine alternative transportation system configurations, while the supporting volumes describe the analysis tools and the calibration data used.

A number of mathematical models were developed and applied. An econometric model was used to predict future changes in population density, employment, personal income and land use. A demand model of the multiple linear regression type used econometric and other data to predict the overall demand for transportation, and distributed the demand among the various modes. Supply models were developed to describe the characteristics of both the existing and proposed new modes — trip times, costs, frequencies, and access characteristics. Cost models were used for determining not only the levels of capital investment required, but also some of the social and environmental costs. An impact model was developed as an attempt

to determine the effect of transportation system improvements on the region's future development. Given the econometric data for some future time and a proposed transportation network, an iteration was performed using the supply and demand models until a supply/demand equilibrium was reached. At this point the various costs and benefits could be evaluated.

Once developed, the model system was used to evaluate alternative transportation system improvements for the 1975 to 1980 time period. The new modes considered were STOL, VTOL, and several high-speed rail possibilities including the tracked air cushion vehicle (TACV).*

Figure 2.2-1 shows some of the STOL and VTOL vehicle characteristics assumed for the alternative system evaluation runs. The first STOL vehicle considered was the MDC-210G, the proposed commercial version of the MDC-188 (Breguet 941S). Like the Model 188, it uses the deflected slipstream principle and has four mechanically-interconnected propellers; it differs by being larger and faster, seating 122 and cruising at 368 mph. During the evaluation runs, it was found that a smaller vehicle would provide a better match to the Corridor's air transportation needs in the 1975 to 1980 time period over the routes considered and would result in more efficient vehicle utilization. Accordingly, some further runs were made using the DHC-7, a 48-passenger propeller STOL vehicle with a 276 mph cruise speed. The VTOL vehicle considered was the Sikorsky S-65 compound helicopter which seats 86 and cruises at 265 mph. This vehicle seemed well matched to Corridor needs.

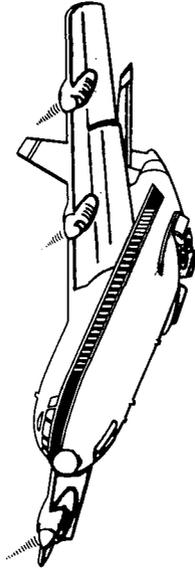
Table 2.2-1 lists the number of daily STOL operations[†] at various air terminals in the Northeast Corridor for three of the evaluation runs.⁶ In the first of these runs, the STOL system uses the MDC-210G and competes with auto, bus, conventional air, and high-speed rail "A" — one of the less expensive high-speed rail alternatives. In the second case, a competing VTOL network with a different set of terminals and routes is added using the S-65. In the third case the MDC-210G is replaced by the smaller DHC-7. Only STOL operations are shown in the body of the table, but

* The analysis and data presented with respect to V/STOL systems in the Northeast Corridor Transportation Project Report have been criticized as overly optimistic in a subsequent report issued by the Department of Transportation.⁵ A particular issue is the cost of providing V/STOL terminals and ATC facilities, which has not been sufficiently considered in the analyses described herein. The traffic levels depicted should therefore be regarded as potential traffic levels achievable given sufficient time, rather favorable economic circumstances, and community and passenger acceptance.

[†]An operation is defined as either a landing or a takeoff. There are presumably an equal number of landings and takeoffs over a day's time, not counting vehicles lost, stolen or strayed.

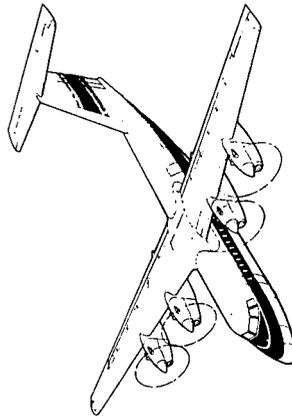
MDC - 210G STOL

122 SEATS MAX.
368 mph CRUISE SPEED
20,000 ft CRUISE ALTITUDE
84,500 lb GROSS WEIGHT
532 mi MAXIMUM RANGE



DHC - 7 STOL

48 SEATS MAX.
276 mph CRUISE SPEED
15,000 ft CRUISE ALTITUDE
37,000 lb GROSS WEIGHT
1250 mi MAXIMUM RANGE



S - 65 VTOL

86 SEATS MAX.
265 mph CRUISE SPEED
8000 ft CRUISE ALTITUDE
63,600 lb GROSS WEIGHT
315 mi MAXIMUM RANGE



Figure 2.2-1 Assumed STOL and VTOL Vehicle Characteristics for the Northeast Corridor Transportation Project (Ref. 6)

Market Area	Site	1975 STOL OPERATIONS PER DAY		
		MDC-210G STOL	MDC-210G STOL competes with S-65 VTOL	DHC-7 STOL competes with S-65 VTOL
Washington	College Park	142	114	242
	Fairfax			
Baltimore, Md.	Towson	80	66	160
Wilmington, Del.	Greater Wilmington	52	42	104
Philadelphia, Pa.	New Media Apt.	64	42	108
	North Phila.	76	74	152
	Wings Field	64	40	118
	Burlington Co.	68	44	124
Trenton, N.J.	Mercer Co.	48	46	110
Newark N.J.	Newark	66	52	132
	Teterboro	50	50	98
New York, N.Y.	57th & Hudson	150	130	280
	La Guardia	88	76	158
	Bethpage	64	46	124
	Westchester Co.	128	82	218
New Haven, Conn.	Bridgeport	78	60	166
	Tweed-New Haven	64	74	146
Hartford, Conn.	Brainard	86	78	176
Springfield, Mass.	Bowles-Agawam	58	42	112
Providence, R.I.	Green	48	40	90
Worcester, Mass.	Worcester	22	20	36
Boston, Mass.	Hanscom	88	66	178
	Norwood			

TOTAL STOL OPERATIONS: 1584 1284 3032

TOTAL VTOL OPERATIONS: 2840 2852

Other Competing Modes: auto, bus, CTOL, high speed rail "A"

Table 2.2-1 Northeast Corridor STOL operations as projected for the Northeast Corridor Transportation Project (Ref. 6)

the total number of VTOL operations is shown along with the total number of STOL operations at the bottom of the table. It can be seen by comparing cases one and two that competition from VTOL is responsible for only about a twenty percent drop in the total number of STOL operations, reflecting the fact that the VTOL network concentrates on shorter stage lengths than the STOL network. A comparison of cases two and three shows that, as might be expected, the number of STOL operations varies inversely with the vehicle seating capacity.

It is particularly interesting to note whether any of the terminal sites in the system would be congested at the operations levels listed in the table. Different types of terminals are involved: STOLports, large and small general aviation airports, and airports having a large percentage of air carrier traffic. The Manhattan STOLport is the busiest, having 280 operations per day in case three. Assuming a peak-to-average-hour* operations ratio of 3 which is a typical number for air carrier operations at the busier airports,⁷ this translates into 35 operations during a peak hour — busy, but not terribly congested. In the case of the air carrier airports, the impact of the indicated STOL operations cannot be assessed without further information about the reductions which have presumably been made possible in short-haul CTOL traffic, and the severity of STOL/CTOL conflicts, a subject which is discussed in Section 3.5 of this report. STOL operations at the larger general aviation airports are likely to be a problem because of existing congestion at peak hours. Peak-to-average-hour operations ratios for these airports tend to be rather large, 5.75 for Teterboro in FY 1969, for example.⁷ In that year, 161 operations were handled in the peak hour at Teterboro, as compared with 124 at La Guardia, even though La Guardia handled 40% more traffic on an annual basis. The safety of STOL operations at the busier general aviation airports is certainly open to question.

Some other projections of STOL traffic levels and vehicular types, will now be considered; specifically, those presented by de Havilland Aircraft of Canada, Ltd., before the Civil Aeronautics Board's Northeast Corridor VTOL Investigation,⁴ an investigation which concerned itself with both STOL and VTOL air service.

Phase one of the Northeast Corridor VTOL Investigation was conducted between October 1967, and February 1970, and concluded that VTOL, STOL or V/STOL intercity air service in the Northeast Corridor is technically and economically feasible on a nonsubsidized basis. It also concluded that the service would be in the public interest "in order to reduce congestion and delay in air transportation and improve the quality of air transportation" in the Corridor. Phase two of the Investigation (in progress as of this writing) is to consider certain regulatory issues, and may include the selection of a carrier or carriers to provide the service.

* Average-hour operations are found by dividing the total daily operations by 24.

Detailed economic analyses supporting the feasibility conclusion were carried out by a number of interested parties, notably, Pan American World Airways, Inc., de Havilland Aircraft of Canada, Ltd., the McDonnell-Douglas Corp., and the Sikorsky Aircraft Division of United Aircraft Corp. The results discussed here are from the de Havilland exhibits.⁴

The methodology of the de Havilland analysis differed somewhat from the supply/demand balancing discussed in connection with the Northeast Corridor Transportation Project. The de Havilland procedure was to extrapolate demand data from the 1960's for the auto, bus, air and conventional rail modes into the 1970's and then use a modal split model to calculate the penetration of a STOL network into this extrapolated demand. This method does not take into account the induced demand that might result from the introduction of a new mode, and should result in conservative estimates in that regard. Competition from high-speed rail and VTOL was not explicitly considered, however.

Figure 2.2-2, taken from the de Havilland exhibit, shows the impact of the STOL service on intercity passenger travel. The figure indicates a substantial patronage for the STOL service, the DHC-7 STOL potential growing from about 6 to 15 million annual passenger trips during the 1970's. The achievable potential shown in the figure is somewhat less, owing to the elimination of certain routes having a low frequency of service.

Table 2.2-2 shows STOL daily operations for three different time periods and for three different vehicle types, the DHC-6 (Twin Otter) seating from 18 to 20 passengers, the DHC-7 seating 48, and an augmentor-wing jet STOL seating 100. An increase in total daily operations is predicted, in spite of the trend toward use of the larger vehicles. Using the 1973 and 1978 data, one might estimate about 2000 daily operations for 1975, considerably fewer than the 3000 indicated for case three of Table 2.2-1. The variance is due to the different assumptions and methods used in the two studies and gives some indication of the range of uncertainty involved.

It is again interesting to examine the traffic levels indicated in Table 2.2-2 for possible congestion problems. Except for the two Manhattan STOLports, the STOLport daily operations levels listed in the table should not lead to serious congestion — the peak hour operations rates calculated as before are all less than 35 per hour. The Manhattan STOLports, however, jointly handle between 50 and 80 operations during peak hours and may present some difficulties, depending on the adequacy of the STOLport design and the operational procedures employed. Operations at the larger general aviation airports, such as Hanscom Field, may also present problems as noted previously. Air carrier airports were not used as sites in the de Havilland study.

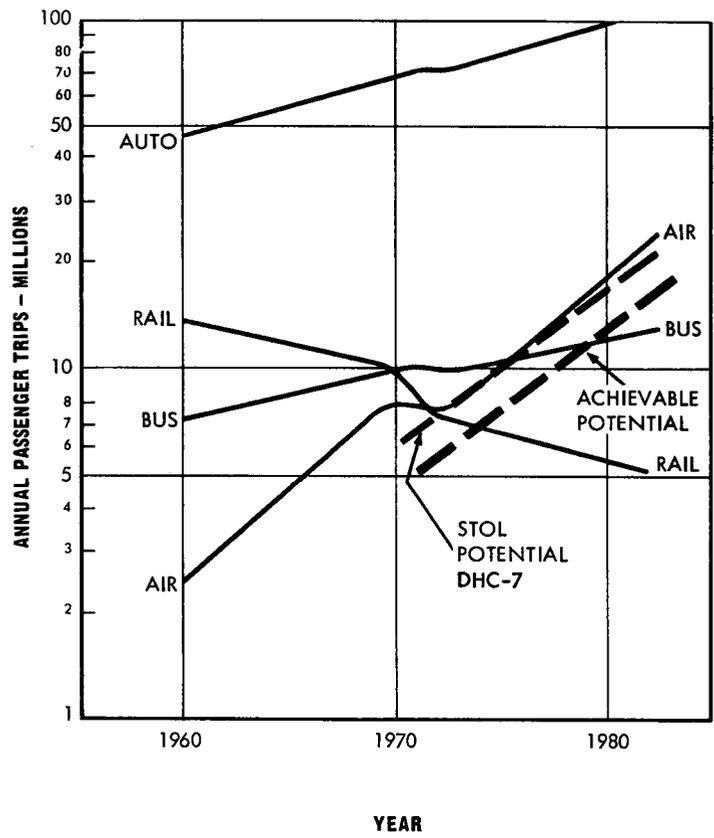


Figure 2.2-2 Total Intercity Passenger Travel—35 City Pairs (Ref. 4)

Market Area	Site	STOL Operations Per Day		
		1973	1978	1982
Washington	Union Station	123.8	189.6	226.8
	Potomac Site	20.0	42.6	59.4
	Bethesda	42.6	92.8	97.0
	Alexandria	23.0	71.8	86.6
Baltimore, Md.	CBD	62.4	86.8	123.2
Wilmington, Del.	CBD	14.2	14.4	15.6
Philadelphia, Pa.	CBD	99.6	122.2	181.6
	West Phila.	49.4	87.2	115.0
	North Phila.			27.0
Trenton N.J.	Mercer Co.	39.8	59.0	64.6
Newark, N.J.	Passaic	47.2	70.0	126.0
New York, N.Y.	Manhattan West	400.0	352.4	295.6
	Manhattan East		274.0	346.8
	Governors Island	9.6	36.8	82.4
	Queens	102.2	143.6	185.8
	Westchester Co.	114.0	182.4	183.0
Hartford, Conn.	Brainard	87.4	100.4	109.6
Providence, R.I.	CBD	49.4	71.8	124.8
Boston, Mass.	CBD	113.6	212.4	255.2
	South Weymouth	60.2	105.6	106.0
	Hanscom Field	60.0	107.4	92.6
	Beverly	7.2	32.4	50.2

DHC-6 OPERATIONS:	452	388	392
DHC-7 OPERATIONS:	1076	2068	1204
AUGMENTOR WING OPERATIONS:			1360
TOTAL DAILY OPERATIONS:	<u>1528</u>	<u>2456</u>	<u>2956</u>

Competing Modes: auto, bus, CTOL, rail

Table 2.2-2 Northeast Corridor STOL operations as projected for the Northeast Corridor VTOL Investigation (Ref. 4)

One other feature of the data which should be noted is the relative persistence of the market for the smaller STOL vehicles, leading in time to a considerable disparity in the sizes of vehicles operating from a given STOLport. This is, of course, a familiar airport phenomenon.

In summary, the data listed in Tables 2.2-1 and 2.2-2 give an indication of the potential characteristics of intercity STOL traffic, the traffic levels, vehicle types, and the traffic mix. Potential congestion problems are indicated at a few, high-density, city-center STOLports, e.g., New York; at heavily-used general aviation airfields, e.g., Teterboro or Hanscom Field; and possibly at air carrier airports, if these are used for STOL air service.

References for Section 2.2

1. University of Toronto, Institute for Aerospace Studies, An Assessment of STOL Technology, A study prepared for the Canadian Transport Commission, Research Division, UTIAS Report No. 162, 1970.
2. Nelson, Robert A., et.al., Northeast Corridor Transportation Project Report, NECTP-209, N70-34648, PB 190929, 1970.
3. Civil Aeronautics Board, Northeast Corridor VTOL Investigation, Initial Decision of Examiner E. Robert Seaver, Docket 19078, February 2, 1970.
4. De Havilland Aircraft of Canada, Ltd., Exhibits Before the CAB, Northeast Corridor Investigation, 1969.
5. Miller, Myron, et.al., Recommendations for Northeast Corridor Transportation, 3 Vols., Final report issued by the Department of Transportation, May 1971.
6. Roberts, Michael J. and Goldman, Donald, Air Mode Service Analysis in the Northeast Corridor, NECTP-215, N71-11029, PB 190935, MTR-4113, 1969.
7. Federal Aviation Administration, Terminal Area Air Traffic Relationships, Office of Management Systems, Information and Statistics Division, 1969.

2.3 ATC SYSTEM DESCRIPTION

The design of suitable avionics and flight control systems for STOL vehicles requires, in part, a description of STOL air traffic control procedures — the more detailed the better. However, it is unlikely that STOL procedures will be finalized until some form of STOL service is actually introduced, given the invigorating nature of practical operating experience. In the interim, projections must be based on current procedures, the expected evolution of the ATC system, and any special STOL operating requirements that can be identified.

The point of view taken herein is that STOL operations should be designed to interface with the expected evolution of the ATC system. STOL air traffic control should, wherever possible, be based on the same general principles and procedures as CTOL air traffic control. This conclusion is based on the following lines of reasoning:

1. The development of totally new ATC systems for STOL operations would be a costly proposition. It is not reasonable to expect such development costs to be borne by the STOL system operators with their possibly risky financial situation, or by the federal government which is facing current ATC system costs of 18.2 billion dollars for the next decade.
2. If a "better" air traffic control system is being proposed for STOL operations, then why not develop it for all users, CTOL and STOL alike. Advanced avionics can be used by both classes of users. The development of a common ATC system for air carrier, military and general aviation was found to be a practical and economic necessity. STOL will similarly require a common-system approach.

This is not to say that special procedures will not exist for STOL operations. Such procedures may arise as a result of the slow approach speed and high maneuverability of the STOL vehicle, or because of operational problems in certain terminal environments. Such special procedures must be designed so as to cause minimal disruption of current system and expected future system operation.

Air traffic control will be discussed from a functional point of view in Section 2.3.1. The current system is then discussed in Section 2.3.2, and the expected system evolution in Section 2.3.3. Some aspects of STOL operations within the context of the ATC system are discussed in Section 3.5.

2.3.1 Functional Description

The objectives of an air traffic control system are to provide a safe, expeditious flow of air traffic at a minimum system operating cost.

A dichotomy exists between "safe" and "expeditious". A safe system uses large aircraft separation criteria to avoid collisions whereas an expeditious system uses small separation criteria to obtain a high rate of flow. The tradeoff between safety and capacity has rarely been made in a systematic manner.

With the possible introduction of advanced avionics equipment as an integral part of the STOL aircraft into the ATC system, it is useful to review the ATC system from a general point of view in order to see the STOL craft and its associated equipment in proper perspective. This view should allow a more realistic judgment to be made of improvements in safety or capacity which may result from STOL system use.

The following definitions will aid in the construction of an ATC overview:

\underline{F}_i : is a flight plan vector associated with aircraft i which describes the expected flight path.

\underline{P}_i : is a position vector for aircraft i.

The ATC system works by exercising control over three quantities:

- 1) $(\underline{F}_i - \underline{P}_i)$: Flight Plan Deviation. This is the ATC Guidance Loop.
- 2) $(\underline{F}_i - \underline{F}_j)$: Flight Plan Separation. This is the ATC Conflict Loop.
- 3) $(\underline{P}_i - \underline{P}_j)$: Position Separation. This is the ATC Hazard Loop.

To facilitate this task, controlled airspace is divided into traffic sectors. Associated with each sector are:

- 1) one or more traffic controllers
- 2) a communications channel
- 3) the controlled aircraft within the sector boundaries

The sector controller's job is to generate a set of compatible \underline{F}_i 's, and then to monitor flight plan deviations and position separations. The controller obtains information about aircraft position by means of the Data Acquisition System (DAS). The communication channel is used to transmit the \underline{F}_i 's to the aircraft, and may be subject to transmission error and delay.

At the aircraft level, three additional control loops exist:

- 1) The Aircraft Control Loop. The speed, heading and rate of climb are controlled by the pilot/autopilot using commanded inputs of, primarily, δ_a (aileron angle), δ_e (elevator angle), and T (engine thrust). This loop, then, controls the velocity vector of the aircraft.
- 2) The Aircraft Guidance Loop. The value of $(\underline{E}_i - \underline{P}_i)$ is fixed by the pilot through control of the velocity vector. The adequacy of the guidance loop is determined by the value of $(\underline{E}_i - \underline{P}_i)$. Position is determined onboard the aircraft by means of the Aircraft Navigation System (ANS_i).
- 3) The Aircraft Hazard Loop. The value of $(\underline{P}_i - \underline{P}_j)$ is determined by the pilot either visually or using electronic hardware. The means for determining the relative position will be designated the Collision Avoidance System (CAS_i). By observing the proximity of other aircraft, the pilot can decide on a modified flight plan to minimize a collision threat. This is a backup loop under IFR conditions, as the ground ATC system has primary control in that case. Thus the airborne hazard criteria are less severe than the ground criteria. (The revision of \underline{E}_i by the pilot may require some communication back to the ATC sector controller.)

Figure 2.3-1 summarizes the general ATC system described above.* The figure shows the traffic sector control on the left (designated s) interacting with aircraft i and aircraft j on the right by means of the communication channel. The various control loops are indicated. The superscript i is used to designate information obtained by an aircraft using its own equipment. The superscript s denotes information obtained by the Data Acquisition System and used by the traffic sector control. When no superscript is shown, the true value of the quantity is indicated.

Thus it can be seen that the primary improvement that STOL airborne equipment will bring will be a tightening of the aircraft loops, which may not necessarily improve the total ATC system in either capacity or safety. It is only if concomitantly the outer control loops are improved that a system-wide improvement will result.

2.3.2 The ATC System Today

This section will outline the current implementation of the ATC process by means of regulations, procedures, and active control facilities. Various activity phases are identified and the operation of the en route and terminal traffic control facilities are reviewed.

* Source: Robert W. Simpson, Class Notes for ATC, M.I.T. Aeronautics and Astronautics Graduate Course 16.601, Spring, 1971.

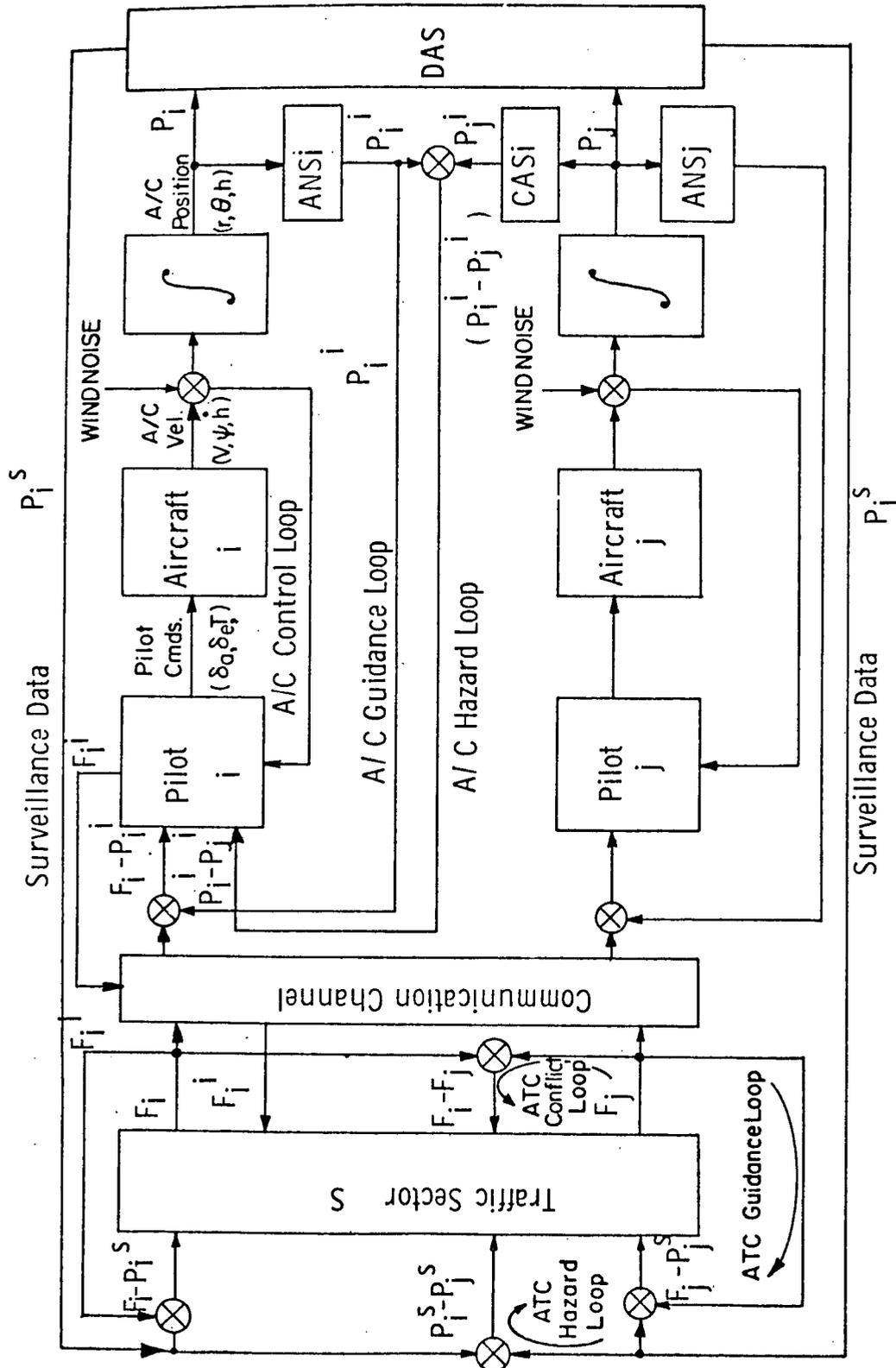


Figure 2.3-1 A General ATC System Diagram

The ATC system that exists today has evolved over the years in response to technological advances in the field of flight transportation. In 1930 the first control tower was established at Cleveland; in 1935 the first ATC center was manned at Newark by the airlines. It was not until 1936 that the federal government assumed responsibility for the centers. The Federal Aviation Administration (FAA) was created and given responsibility for the ATC system by the Federal Aviation Act of 1958.

The Federal Aviation Regulations distinguish between two types of aircraft: controlled and uncontrolled, or, in FAA terminology, IFR and VFR. For VFR aircraft, the legal responsibility for avoiding a collision rests with the pilot. For controlled aircraft, the legal responsibility for avoiding collisions with other controlled aircraft rests with the ATC controller; for uncontrolled aircraft the responsibility rests with the pilot.

Current rules prohibit VFR operations if the visibility is less than one mile in uncontrolled areas. In controlled areas visibility must be greater than 3 miles below 10,000 feet and greater than 5 miles above 10,000 feet. VFR aircraft must have 1,000 feet vertical separation and 2,000 feet horizontal separation from clouds. Below 10,000 feet the maximum allowable indicated airspeed is 250 knots for all aircraft. All traffic is controlled above 18,000 feet in the Golden Triangle (Chicago, Boston, Washington) and above 24,000 feet elsewhere in the United States and must have an operating radar beacon transponder and a two-way radio before being permitted to operate at these altitudes.

Five distinct activity phases can be identified in the ATC system:

- 1) Gate Activity Control (the Operations Desk): has responsibility for the pre-flight activities. The pilot files his flight plan, obtains the weather forecast and other information and gets clearance.
- 2) Ground Control: has responsibility for taxiways and all ground vehicles. It is located at the top of the control tower (the cab).
- 3) Tower Control: has responsibility for clearing takeoffs and landings, and for aircraft operations within 5 miles of the airport (essentially to the outer marker).
- 4) Approach/Departure Control: has responsibility for traffic below 10,000 feet from 5-50 miles away from the airport. It is located in the common IFR room or Terminal Radar Approach Control Facility (TRACON).
- 5) En Route Control: has responsibility for all IFR traffic en route. It is located in the Air Route Traffic Control Center (ARTCC). The current trend is to enlarge TRACON responsibility and thus not to bother the centers with near-terminal activity.

The responsibility at an ARTCC is divided into sectors. The primary division is between high-altitude sectors and low-altitude sectors. Each sector is assigned to a controller. The sectors are structured so as to have at most two airways and two frequencies. Each controller can talk to the pilot and vice versa; the pilots have to change frequencies when they move from sector to sector. The hand-off of an aircraft from center to center is handled via phone link. Currently there exist 21 FAA ARTCC's within the coterminous United States and six additional centers outside.

At the terminal control facility, the responsibility is usually divided by means of assigning different controllers to handle arrivals and departures.

Of particular interest for STOL operations (see Section 3.5.3) is the new "keep 'em high" procedure being implemented at major hubs to provide a more effective means for segregating IFR aircraft from VFR aircraft. The reason for the policy is that the most hazardous mix of controlled and uncontrolled aircraft occurs in the terminal areas at altitudes up to 4000 feet.

"Under its terms all turbojet arrivals shall enter the Boston Terminal Airspace via established outer clearance limits and shall operate at 10,000 or above until within Boston Terminal Airspace and on Boston Approach Control frequency. Such aircraft will be reduced from cruise speed to 250 knots 10 miles prior to reaching the outer fix. After leaving the outer fix, such aircraft will not be descended below 5,000 feet until they are within the descent area for the appropriate airport and runway to be used. Once in the descent area, a normal rate of descent will begin and terminate at landing. We continue to solicit cooperation in noise abatement efforts by suggesting that aircraft maintain not below 3,000 feet for as long as practicable but certainly not beyond the 10-mile point on final.

Departing aircraft will be climbed to the highest possible altitude filed as soon as possible after departure."¹

The ATC system is currently in the process of transition to the so-called Third Generation System. For the Third Generation System the FAA is implementing (1) limited automation to assist the controller, and (2) automated data acquisition through the Air Traffic Control Radar Beacon System (ATCRBS).

The automation for the ARTCC's is the National Airspace System (NAS) Stage A program which provides greater traffic handling capability and improves safety.

At the top 64 terminal facilities (out of 117 that are radar equipped), the Automated Radar Terminal System (ARTS III) program is being implemented. These terminals handle over 80% of the commercial passenger operations and 70% of the total instrument operations. Approximately 60% of the general aviation fleet is based in these areas. The initial operating capability of ARTS III is the digitizing,

processing, and display of alphanumeric data associated with transponder-equipped aircraft. The system is modularly expandable; the number and type of functions implemented at a given terminal depends on the operational requirements at that facility. NAS and ARTS automation is expected to increase capacity of the control sectors by 20%.

2.3.3 Evolution of the ATC System

The present section is a discussion of the expected evolution of the ATC system as derived from the recommendations of the Department of Transportation's Air Traffic Control Advisory Committee,² FAA plans and policy statements, and work in progress on system improvements.

The Advisory Committee's recommendations were aimed primarily at upgrading the Third Generation ATC System — the System currently being implemented — to allow it to handle increased traffic levels. The Committee also recognized that changes of a more radical nature leading to a Fourth Generation System would probably be necessary in the post-1990 time period. Most of their recommendations for upgrading the Third Generation System have been embodied in the FAA's research and development plans for the 1970's. Work leading to the definition of Fourth Generation System concepts is currently in progress.

Table 2.3-1 summarizes the Advisory Committee's recommendations for improving the Third Generation System. Their suggestions included a number of methods for increasing airport and terminal-area capacity, the concept of intermittent positive control (IPC) for improved separation assurance, various automation schemes, modifications to the present ATC Radar Beacon System (ATCRBS) to provide for a data link and enhanced data acquisition system capability, and proposals for improved navigation and landing aids on the ground coupled with the extensive use of airborne area navigation equipment. Some of the more recent developments in the plans for terminal-area automation are discussed in the paragraphs below. The developments are based on the NAS/ARTS hardware and software and will lead to the eventual use of the data link for transmitting ATC commands.

FAA plans for implementing the recommendations of the ATC Advisory Committee in the areas of communications and automation are shown in Fig. 2.3-2.³ Data link feasibility tests on the modified ATCRBS and alternative systems should lead to a system selection in about 1976, followed by prototype development. The automation plans call for completion of metering and spacing and IPC software development by 1974. This is to be followed by development of the data link interface, integration with NAS/ARTS, and field implementation during the late 1970's.

Terminal capacity improvements
<ul style="list-style-type: none"> -Dual lane runways -Decreased aircraft longitudinal separation -Decreased separation between independent IFR parallel runways -Curved approaches
Separation
<ul style="list-style-type: none"> -Intermittent Positive Control
Automation
<ul style="list-style-type: none"> -Automatic spacing, sequencing, and conflict resolution using NAS/ARTS -Use of data link
Data acquisition/Data link
<ul style="list-style-type: none"> -Phased-array interrogators for Beacon -Discrete address mode for Beacon
Navigation and landing aids
<ul style="list-style-type: none"> -Upgraded VOR/DME system and use of area navigation -Scanning-beam microwave ILS

Table 2.3-1 Summary of ATC Advisory Committee Recommendations for Upgrading the Third Generation ATC System (Ref. 2)

Landing interval and time-to-fly calculations

Scheduling: first-come-first-served basis with slip-forward, slip-back, and revised-landing-sequence logic

Direct Course Error (DICE) to various control points

Multiple-runway operation capability

Simultaneous-altitude-occupancy warning

Automatic metering-information exchange with en route control

Provision of schedule gaps in arrival sequence for departures

Variable approach-gate location

Runway configuration change

Rescheduling and sequencing of missed-approaches

Real-time wind estimation

Table 2.3-2 Features of ARTS III Computer-Aided Metering and Spacing (Ref. 4)

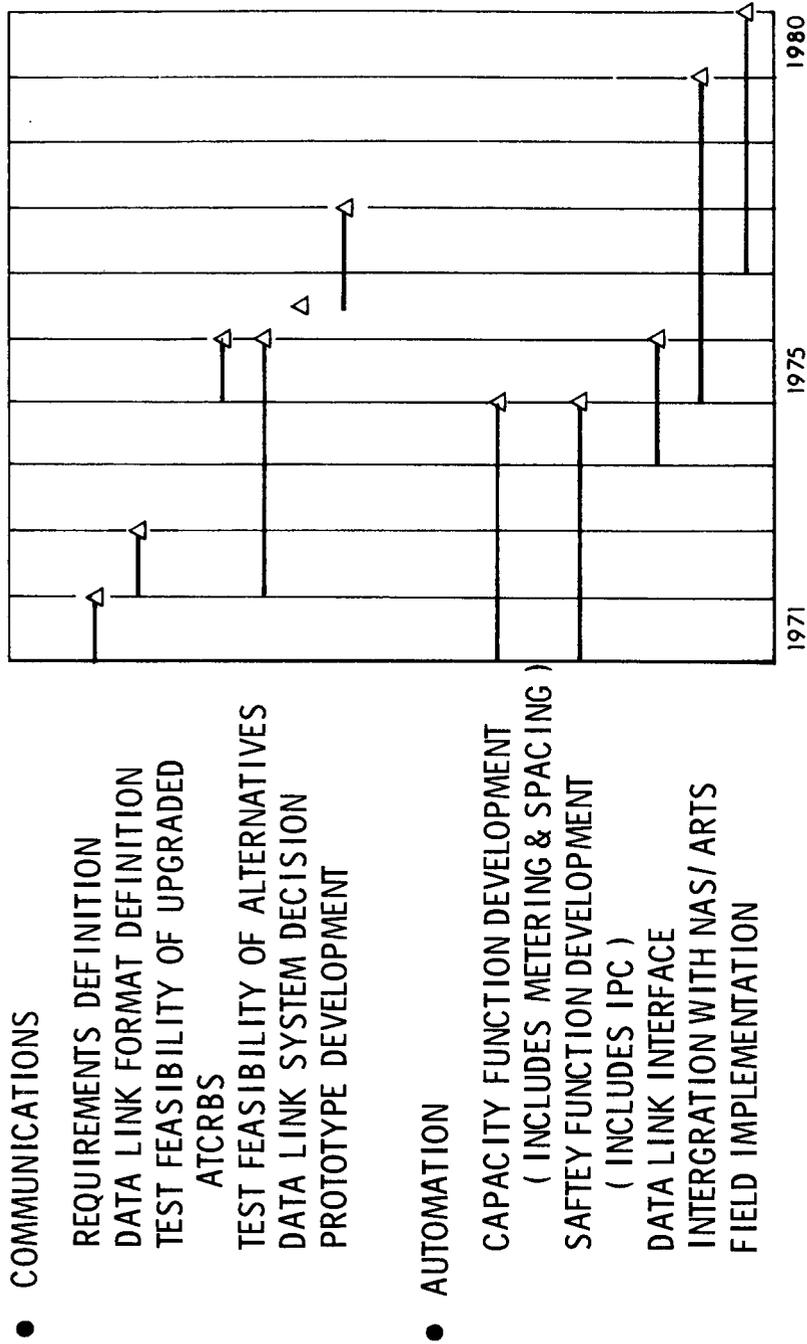


Figure 2.3-2 FAA Development Plans for Communications and Terminal Area Automation (Ref. 3)

If the planned automation proves successful and the current schedule is maintained, some of the earlier STOL operations — in the late 1970's — might be expected to take place within the context of the automated metering and spacing system, at least in the busier terminal control areas. For this reason, we turn now to an examination of the automation plans as discussed in a recent report prepared for the FAA.⁴

The automation plans discussed in the report are based on work carried out mostly under the direction of the federal government during the past 25 years. Extensive real-time simulation of various automation concepts was carried out at the National Aviation Facilities Experimental Center (NAFEC) in the early 1960's leading to field trials at Atlanta in 1966 and at New York in 1966 and 1967. Field testing of the revised system concepts and new software, designed to interface with the ARTS III computers and displays, is planned for Atlanta in the near future.

Table 2.3-2 lists some of the features of the ARTS III computer-aided metering and spacing plan. The computer calculates the minimum landing intervals required between arriving aircraft based on aircraft type, expected runway occupancy time, desired speed on final approach, and so forth. As the aircraft approach the terminal area, the time-to-fly to the runway threshold is calculated and used together with the landing interval information to schedule the aircraft on a first-come-first-served basis. The scheduling is flexible and incorporates slip-forward, slip-back, and revised-landing-sequence logic should this become necessary during the approach. The primary method used to control the aircraft time-of-arrival at the approach gate and various intermediate fixes is geometric — path stretching and shortening. The computer displays to the controller the direct course error, the error in the time-of-arrival at a given fix which is calculated to occur should the aircraft turn and fly directly to the fix. The controller uses this information together with his own judgment to issue heading commands to the aircraft. When fully developed, the system should be able to handle simultaneous multiple-runway operations.

The automated system provides a limited collision-avoidance function in the form of a simultaneous-altitude-occupancy warning which is displayed to the controller.

One feature of particular importance is the automatic exchange of metering information with the en route control center which should allow the center to adjust the flow rate into the terminal area to correspond to existing and projected runway acceptance rates.

Another valuable innovation is the provision of schedule gaps in the arrival sequence to allow for departures. Arrivals normally have priority over departures which causes severe departure delays during peak hours. The automated system

allows the controller to input a desired arrival/departure ratio and then schedules gaps in the arrival sequence to allow the ratio to be realized.

Further flexibility is provided to the controller by allowing the approach gate location to be varied depending on conditions. The approach gate (marking the beginning of the final-approach path to the runway), which might be 5 to 10 miles from the runway under IFR conditions, can be moved closer for more efficient VFR operations.

Other capabilities of the automated system include a provision for runway configuration changes when deemed necessary by the controller, automatic re-scheduling and sequencing of missed approaches, and real-time wind estimation to update the wind data needed for time-to-fly calculations.

Figure 2,3-3 shows the typical geometry as used in the computer-aided metering and spacing plan. Passage of standard feeder fix locations (holding points when holding is necessary) marks the entry into the terminal area. Large sequence areas are provided in the approach zone leading to the inner fix for coarse time-of-arrival control (± 2 minutes), while a smaller area is set aside on the base leg for fine-tuning (± 1 minute). The nominal path shown is the path that would be flown with the aircraft on-time and calculated to make its schedule. This path can easily be lengthened or shortened as required. The aircraft will normally stay at feeder-fix altitudes for as long as possible, beginning the descent to final-approach altitude at some point in the sequence areas. Several standard speed reductions based on aircraft type are issued by the controller, with the time-of-issuance providing additional control capability if needed. Once again, the computer assists the controller by providing suggested descent and speed reduction commands.

In the metering and spacing scheme described, the computer role is limited to controller assistance through the display of suggested commands and other information. With the addition of a data link capability, however, the computer role can be expanded as warranted to include transmission of commands directly to the aircraft, subject to controller approval.

Inasmuch as plans for upgrading the Third Generation ATC System call for encouraging the development of airborne area navigation capabilities (see Table 2.3-1), it is reasonable to ask whether or how these capabilities might be used by an automated ATC system of the future. Area navigation systems having time-of-arrival control capabilities (4-D RNAV) are being considered for both V/STOL and CTOL ATC applications. Are such systems compatible with the automated metering and spacing concepts discussed above? Would such an airborne capability benefit the currently-planned ATC system automation? The answers are almost certainly "yes", but these questions have not as yet been adequately considered.

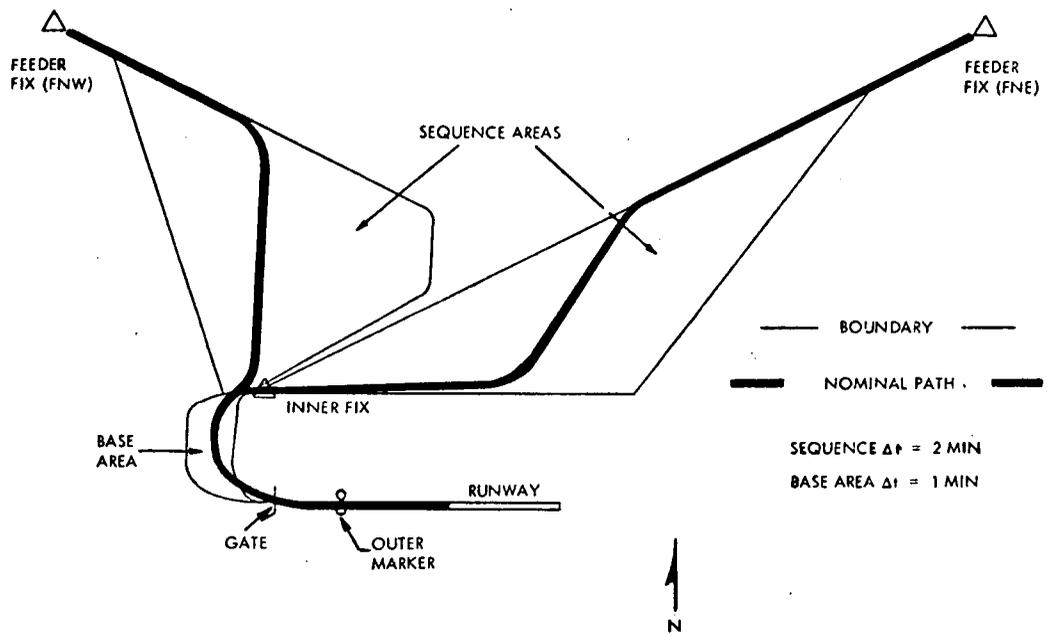


Figure 2.3-3 Metering and Spacing Geometry Plan (Ref. 4)

The use of 2-D, 3-D, or 4-D airborne area navigation capabilities for terminal ATC is complicated by two factors. The first is the need (at least for CTOL) for both equipped and unequipped aircraft to be able to make use of a common ATC system. System concepts which require the segregation of RNAV CTOL traffic from non-RNAV CTOL traffic would be difficult to implement and manage because of the shortage of airspace surrounding busy airports.

The second factor is the need for the ground controller to be able to monitor the performance of RNAV-equipped aircraft in executing preplanned or commanded flight paths and to be able to intervene in the case of RNAV malfunction. When a 4-D RNAV-equipped aircraft gets behind schedule, it must make up the time in some standard fashion, using algorithms which can be monitored both in the air and on the ground.

The main benefit to the terminal ATC system of utilizing airborne RNAV capabilities would be a reduction in controller/pilot communication, i.e., vectoring and speed change commands and acknowledgements. For this purpose, a 4-D RNAV system would clearly be superior if the above-mentioned difficulties can be overcome. In addition, the tighter control of the aircraft made possible by the use of an airborne system (assuming satisfactory navaid signal inputs) might enhance the efficiency of the terminal control process.

The use of 4-D RNAV systems in terminal ATC, whether for STOL, VTOL or CTOL, is a subject which should be examined in more detail. Particular attention should be given to methods for using airborne RNAV systems within the context of planned ground-based automation.

References for Section 2.3

1. Logan International Airport Control Tower Bulletin 71-2, 10 May 1971.
2. Department of Transportation, Report of Department of Transportation Air Traffic Control Advisory Committee, Vols. 1 and 2, 1969.
3. Federal Aviation Administration, R&D Plan to Increase Airport and Airway System Capacity, AD707186, 1970.
4. Computer Systems Engineering, Inc., Computer-Aided Metering and Spacing with ARTS III, FAA-RD-70-82, AD718355, 1970.

CHAPTER 3

OPERATIONAL PROCEDURES

3.1 INTRODUCTION

This part of the report examines a number of operational aspects of STOL transportation systems which relate to avionics requirements. The areas of interest are (1) flight paths for noise abatement, (2) the atmospheric environment, (3) approach and landing considerations, and (4) the ATC interface. The analysis in each area is preliminary and should be carried further prior to the required flight test and demonstration programs.

The noise impact of STOL operations is examined in Section 3.2 using PNL, EPNL, and NEF contours. Of these measures, none is considered a perfect predictor of community response, but NEF has been correlated with noise complaints for present airport operations, and the extension to STOL operations seems reasonable. Single-segment approach and departure flight paths are examined, as well as a two-segment departure employing a thrust cutback. The possible reductions in annoyance are described for vehicles with two reference noise levels.

Several important aspects of the atmospheric environment—turbulence, winds, and visibility—are discussed in Section 3.3. Important physical parameters and relationships are reviewed, and turbulence models are compared. Data from the National Climatic Center is presented for some particular airfields showing wind and runway crosswind distributions and ceiling/visibility correlations. These statistics are useful in predicting how often a particular vehicle/avionics combination would be unable to complete an operation at a given airfield, or how rough the ride might be.

A brief examination of the final-approach landing aid interface is presented in Section 3.4, showing the geometry involved in intercepting the localizer and glide slope. A simple model is used, consisting of a straight line segment followed by a constant radius turn which terminates on the extended runway centerline. This type of analysis can help in determining possible approaches to existing fields, or can help in equipping new fields to accommodate desired approaches.

The interaction of STOL aircraft with the ATC system, discussed in Section 3.5, is of prime importance in establishing a working short-haul system. There are several aspects of interest here. Runway capacity is shown in a brief analysis

to be strongly dependent on the separation distance required on landing approach. The approach airspace will probably be the bottleneck for high capacity STOLports, rather than the runway itself.

Discussion is included on the problems of operating STOL aircraft at existing jetports, existing suburban airfields, and separate STOLports. The need for and desirability of STOL operations at jetports is discussed, and methods for conducting such operations on a noninterfering basis are explored. A review is made of previous FAA simulation results and studies pertaining to terminal area, STOLport, and suburban airport operations. Problem areas which might impact avionics and ground system requirements are identified.

3.2 NOISE

Probably the primary constraint on STOL operations will be the noise impact on the surrounding neighborhood. Over the past five years or so, as jet aircraft have proliferated, airport neighborhoods have become increasingly resentful and today are ready and able to stall or block the expansion of air services. This has been clearly demonstrated in New York by the Chelsea neighborhood's refusal to allow a STOLport to be built along the Hudson River,¹ and in Boston by the failure of the Massachusetts Port Authority to get approval for the addition of a major runway at Logan International Airport.

Noise is not the only factor in personal annoyance at aircraft operation, but it seems to be the dominant one. In a recent study and public opinion survey conducted by TRACOR Incorporated,² additional factors were isolated which seemed to play a part in expressed annoyance. The list of additional factors includes:

- a) fear of aircraft crashing in neighborhood
- b) susceptibility to noise
- c) distance from airport
- d) noise adaptability
- e) city of residence.

Still other factors probably play their part in people's resentment, such as ground traffic congestion, pollution, and the feeling that the establishment is making one further encroachment on their territory.

Nevertheless people are aware that air transportation is a "good". Of the questions asked in the TRACOR opinion survey, the query "Do you feel that air transportation is the only practical way of long-distance travel?" brought a yes response from 80% of the people interviewed. However, the response to questions such as

- a) "Do you think the airport is operated in such a way as to serve the best interest of the entire city?";
- b) "Can this city be proud of the services its airport provides to both the community and to its clients?" and
- c) "Do the advantages to the community from having a large airport far outweigh any disadvantages?"

received favorable responses from somewhat smaller majorities — 63%, 73%, and 66% respectively. This sentiment, coupled with the increasing demand for travel (see Section 2.2) seems to indicate that if the major annoyance factors in aircraft

operations can be eliminated or diminished, additional air service would be embraced as an enhancement of a community's life style, rather than be viewed as a detracting element.

That STOL can make vast improvements in the "good neighbor" rating of an air terminal is doubted by few people who can view the situation objectively. The use of new quiet engines, coupled with high maneuverability and steep approach and departure angles make the STOL noise footprints much smaller than the footprints of today's conventional jet aircraft; and this advantage should be maintained, although at a reduced level, when the conventional aircraft are also fitted with quiet engines.

Before looking at STOL noise footprints it is useful to discuss one of the major measures of noise or annoyance, the Noise Exposure Forecast (NEF). It is also useful to examine some of the noise-abating operational procedures developed for today's conventional jet aircraft. This serves as a basis for examining STOL operational procedures in the later pages of this section. The final subsection on noise discusses the application of optimal control theory to the takeoff trajectory of a jet STOL vehicle.

3.2.1 Noise Rating (NEF Method)

Work has been going on during most of this century in trying to define measures of "noisiness" of a sound source. Researchers have been seeking those measurable physical aspects of sound that contribute in a major way to perceived noisiness. In a recent symposium³ Kryter (one of the active researchers in the field) states that to date there appear to be five significant features identified: (1) spectrum content and level; (2) spectrum complexity (concentrations of energy in narrow frequency bands); (3) duration of the total sound; (4) duration of the increase in level prior to the peak level of non-impulsive sounds; and (5) the maximum level reached by impulsive sounds. The noise measures that have found application to aircraft operations over the last decade or so have included items one through three above, as well as corrections for the number of operations and the background noise level (or time of day).

Perhaps the most widely accepted noise measure used in recent years in this country for determining the impact of aircraft operations is the Noise Exposure Forecast (NEF)⁴ given by the following expression:

$$NEF_i = EPNL_i + 10 \log [N_{day} + 16.7 N_{night}]_i - 88 \quad (3.2-1)$$

where, by experimentation, researchers have found that the sampling interval Δt should be about 1/2 sec, and the reference time T_0 should be about 10 sec.⁶ The subscript i refers to the successive samples of PNL. Theoretically the summation would be taken over the interval during which the PNL_i rise from and return to zero. In practice it should suffice to sum over the interval during which the PNL_i rise from a level 10 dB less than the peak, and return to this level again. Alternately one could sum over the interval during which the PNL exceeded some threshold level (e.g., the background noise level).

The second correction, for pure tones or concentrated energy bands, is made by (a) smoothing the spiked SPL-vs-frequency curve, (b) measuring the differences in dB between the peaks in the actual and smoothed curves, (c) picking the maximum of all the differences, and (d) applying the correction factor based on this maximum difference. The correction factor can be as much as 6 PNdB, depending on the magnitude and frequency of the maximum SPL difference. Detailed procedures for computing the EPNL of a noise source are given in Ref. 6.

Although there are other noise measures in use, the NEF measure is especially useful because there are a number of studies^{2,4,7,8} which use it in evaluating the effect of aircraft operations on airport neighborhoods. In addition the FAA is currently using its main component, EPNL, as a basis for regulations concerning aircraft noise.

The land use compatibility as a function of NEF contours is discussed by Bishop in Ref. 4. The land use recommendations are derived from case histories of noise complaints, speech interference criteria, subjective judgment tests of noise, noise insulation properties of typical buildings, etc. He indicates that for the present day and near future, NEF values should be no higher than 30 for the most sensitive land use groups, which include houses, schools, hospitals, churches, libraries, auditoriums, concert halls, outdoor theatres, etc. New construction for these purposes would not require special acoustic insulation if NEF values remain below about 30. For NEF values up to 35, new construction may require acoustic insulation, and for NEF values greater than 35 new construction is not recommended.

For the above land use class, especially the residential portion, the probability of noise complaints is relatively low for NEF values below 30, whereas more complaints and possible group action may result for NEF values of 30-40. For NEF values near 40 and beyond one might observe vigorous and repeated complaints and concerted group action.

The NEF contours at many existing major airports have been computed in Ref. 8 for present day and near-future air traffic levels. The results show that for major hub airports, the NEF 40 contour can extend out 4 miles or more from the

end of a busy runway, while the NEF 30 contour can extend more than 12 miles in either direction! Figures 3.2-1 and -2 show representative contours for 1970 and 1975 operations at selected airports. The amount of land encompassed by the NEF 30 contour, within which complaints are likely to originate, is startling.

The major reason that aircraft operations are so disturbing today is that the engines themselves are very noisy. In addition, the flight path angles are quite shallow, especially on approach. Representative EPNL measurements of 4-engine turbofan overflights at approximately 1,000-foot altitudes are 115 EPNdB on takeoff and 108 EPNdB on landing approach⁷ as shown in Figs. 3.2-3 and -4. Also shown are these same curves for the so-called "new technology" quiet engines.

3.2.2 Flight Paths for Noise Abatement

Given a vehicle with specified noise characteristics, the ultimate noise impact on the surrounding community can be affected significantly by the choice of flight paths. A number of studies have examined the effects of operational procedures for reducing conventional aircraft noise. These procedures are directed at three main areas: (1) variations in climb angles and flap angle profiles on takeoff; (2) power cutbacks on climbout; and (3) two-segment glide slopes on final approach. Some discussion of these procedures is useful before looking at comparable procedures for STOL.

Reference 7 discusses a simulation study which defined the NEF contours for aircraft operations projected to 1975 at three major airports; New York's J.F. Kennedy, Los Angeles International, and Chicago's O'Hare. Included in this study were not only procedures such as mentioned above, but also the effect of retrofitting aircraft with either acoustically lined nacelles or "new-technology" quiet engines. The operational procedures were examined by themselves and then in combination with the engine modifications.

Table 3.2-1 summarizes the results of this study in terms of reduction of land area within the NEF 40 and 30 contours. Figure 3.2-5 shows the flight profiles used.

The results show that in general the quiet engines are the most effective source of noise reduction (quiet engines plus operational procedures produce up to 60% reduction in land area inside the NEF 30 contour, compared with up to 25% reduction for operational procedures alone). This is especially true since in this study all aircraft used the operational procedures, but only the four-engine turbofan aircraft had the engine modifications. The relative percentages of four-engine aircraft operations at the three airports were Kennedy - 33.1%; O'Hare - 21.6%; and Los Angeles - 33.1%.

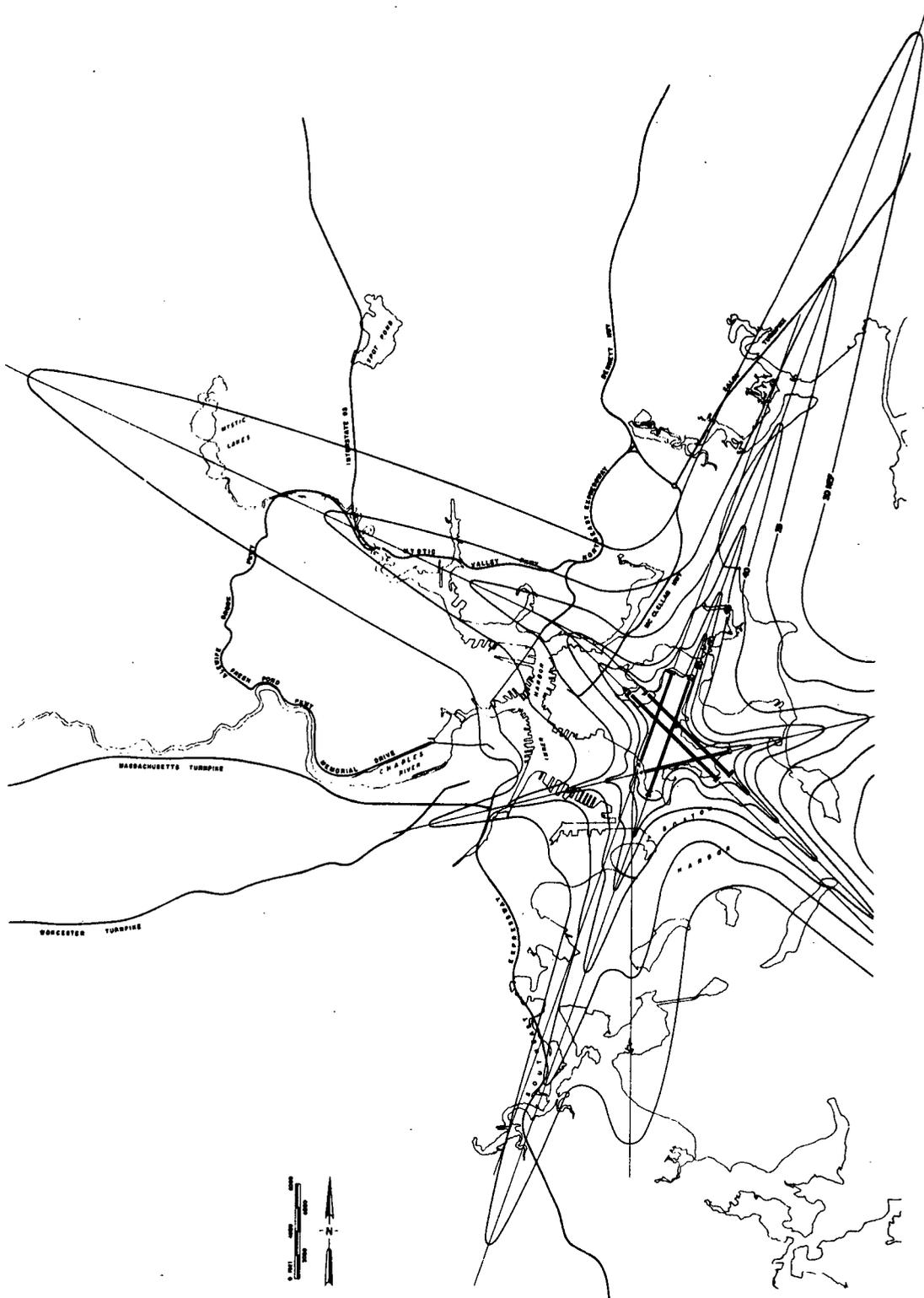


Figure 3.2-1 Noise Exposure Forecast (NEF) Contours for 1975 Operations — Logan International Airport, Boston, Massachusetts (Ref. 8)



Figure 3.2-2 Noise Exposure Forecast (NEF) Contours for 1975 Operations—Dulles International Airport, Washington, D.C. (Ref. 8)

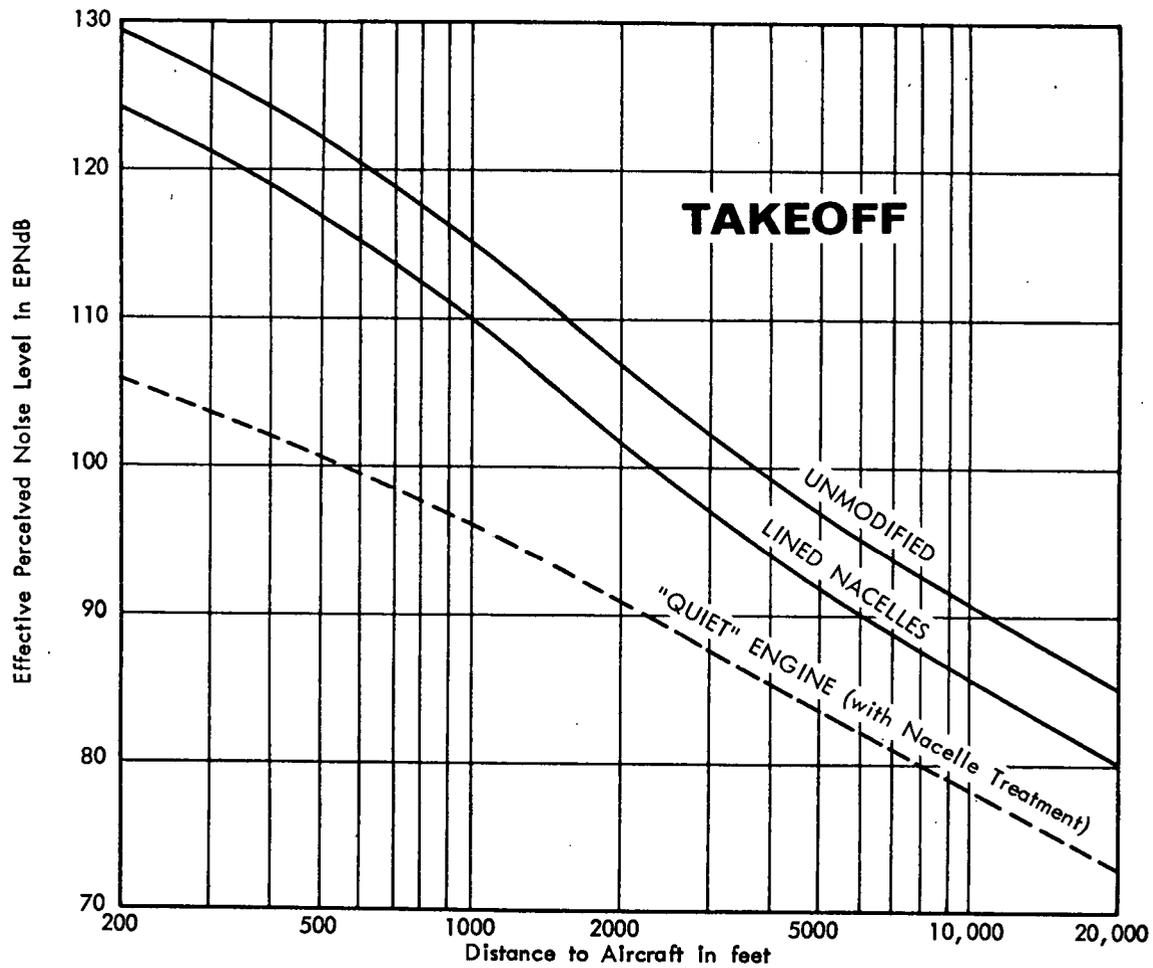


Figure 3.2-3 Effective Perceived Noise Levels—Takeoffs of Large Four Engine Turbofan Aircraft with Retrofits (Ref. 7)

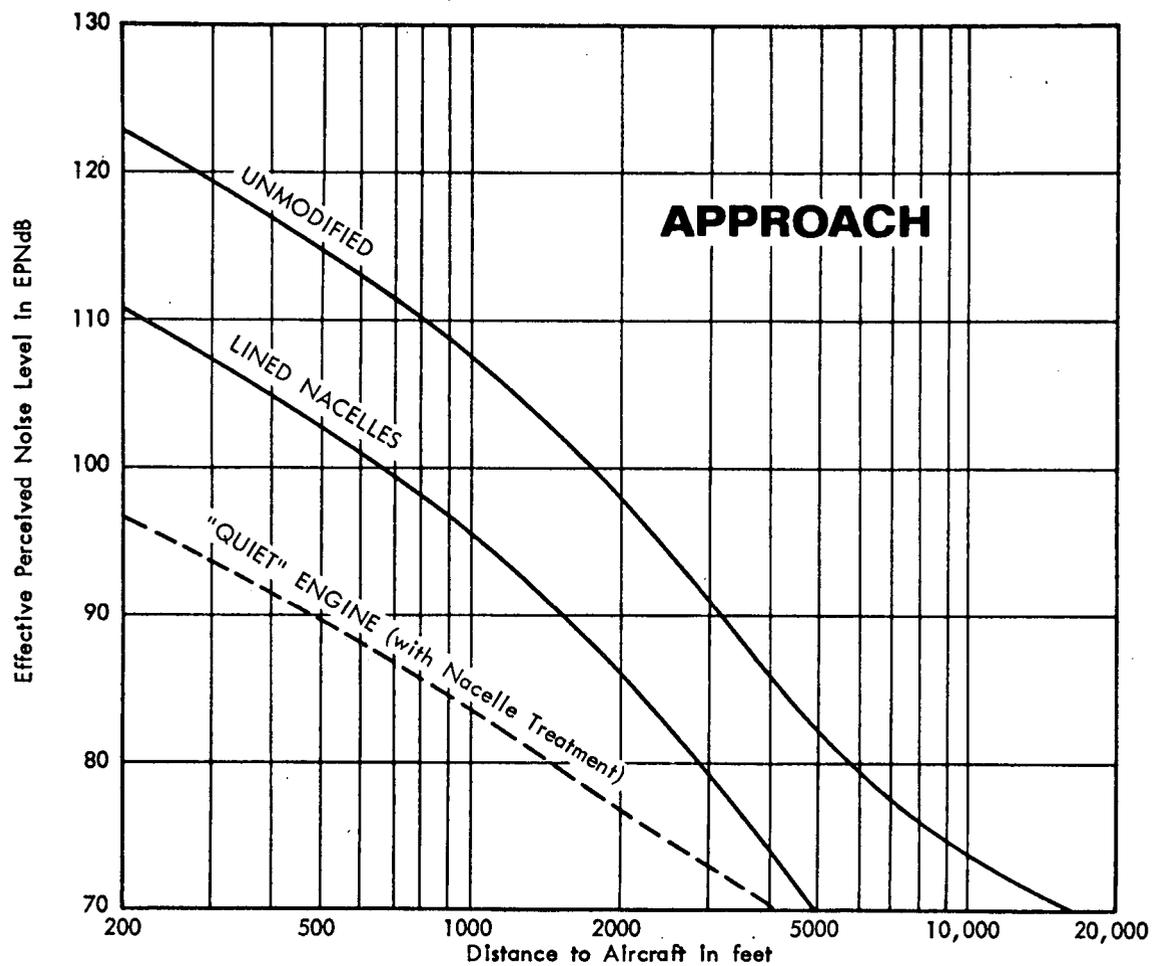


Figure 3.2-4 Effective Perceived Noise Levels—Landings of Large Four Engine Turbofan Aircraft with Retrofits (Ref. 7)

a) LAND AREAS WITHIN NEF 30 AND NEF 40 CONTOURS

Condition	Land Areas in Sq. Mi.					
	O'Hare Chicago		Los Angeles International		J. F. Kennedy New York	
	NEF 30+	NEF 40+	NEF 30+	NEF 40+	NEF 30+	NEF 40+
Baseline	103.6	23.7	33.3	14.4	53.3	14.6
Operational Changes Only	81.6	21.2	25.0	12.9	54.3	13.8
Lined Nacelle Retrofit*	48.5	15.1	19.3	10.0	36.6	9.4
"Quiet" Engine Retrofit*	42.0	13.6	18.9	9.9	30.8	8.4

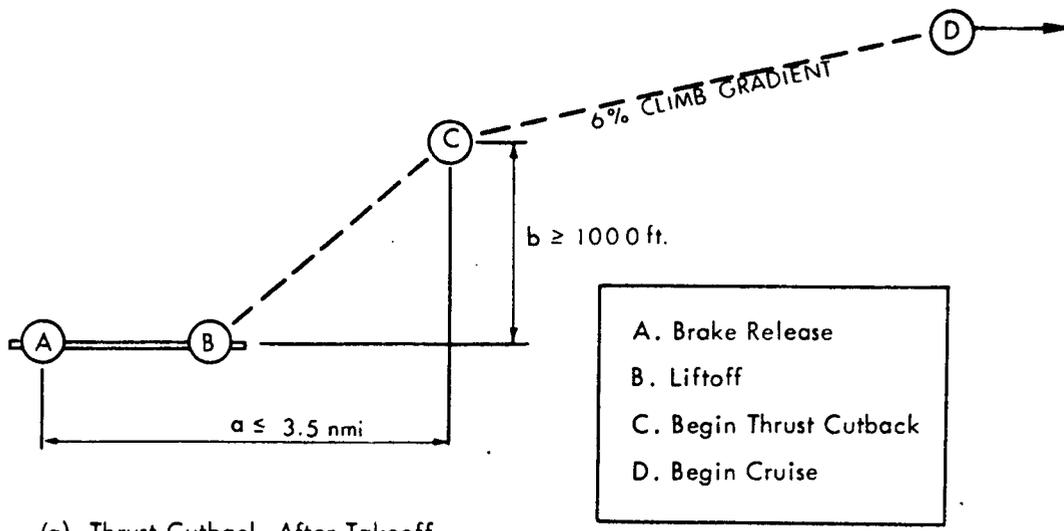
* Includes operational changes for all aircraft, and equipment changes only for four-engine turbofan aircraft (DC-8, 707 types).

b) PERCENTAGE OF LAND AREAS WITHIN NEF 30 AND NEF 40 CONTOURS

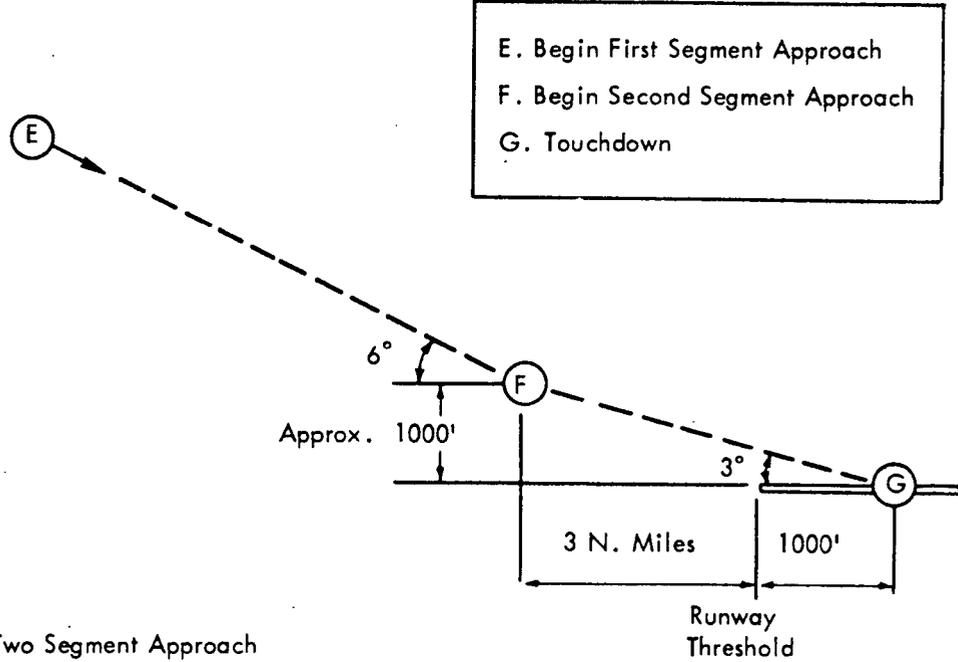
Condition	O'Hare Chicago		Los Angeles International		J. F. Kennedy New York	
	NEF 30+	NEF 40+	NEF 30+	NEF 40+	NEF 30+	NEF 40+
Baseline	100	100	100	100	100	100
Operational Changes Only	78.5	89.5	75.0	89.5	101.9	94.5
Lined Nacelle Retrofit*	47.0	63.5	58.0	69.5	68.7	64.1
"Quiet" Engine Retrofit*	40.5	57.5	57.0	68.5	57.8	57.6

* Includes operational changes for all aircraft, and equipment changes only for four-engine turbofan aircraft (DC-8, 707 types).

Table 3.2-1 Land Area Coverage Within the NEF 30 and NEF 40 Contours at Three Major Airports (Ref. 7)



(a) Thrust Cutback After Takeoff



(b) Two Segment Approach

Figure 3.2-5 Aircraft Flight Profile Modifications (Ref. 7)

Another study, involving simulation and flight test of noise-abating landing approaches, is discussed in Ref. 9. Here a four-engine turbofan Boeing 367-80 (707/KC-135 prototype) was simulated and flown on (1) single-segment approaches of varying glide slope angles, (2) two-segment approaches with two intercept altitudes, and (3) decelerating approaches of one and two segments. The purpose of the study was twofold: (1) to study the effect of operational procedures on ground noise, and (2) to examine the cockpit instrumentation required to make the more complicated flight paths comfortable to fly.

Table 3.2-2 describes the noise abatement profiles flown. Noise measurements were made at three stations situated 1.1, 3.46, and 5.13 nautical miles from the runway threshold. At each station the noise time histories were recorded for later data reduction. A number of different annoyance measures were computed from the basic noise recordings. Figure 3.2-6 shows reductions of up to 18 PNdB in Perceived Noise Level (PNL) for some of the approach profiles run on the simulator. Two of these profiles show flight test measurements for comparison.

A third study^{10,11} optimizes takeoff trajectories for minimum ground noise at some point or area along the flight track. The aircraft considered is again a four-engine jet, but both turbofan and turbojet engines are included. The specific technique employed is a power cutback to produce level flight over the noise sensitive area. The results, an example of which is shown in Fig. 3.2-7, indicate that the distance to the sensitive area determines the climb profile. If the area is close-in (say 3 miles or less) the aircraft should climb at its maximum flight path angle (which requires moderate flap angles) to gain altitude. If the sensitive area is farther out, as illustrated in the figure, it is better to accelerate first to a higher velocity, and then climb. The altitude over the sensitive area will be lower than if the maximum flight path angle had been flown, but the higher speed permits complete retraction of the flaps and thus requires lower thrust to maintain level flight.

3.2.3 STOL Noise Impact

In contrast to the extensive areas contained within the NEF 30 and higher contours for conventional jet operations, STOL aircraft should be able to operate with minimum noise impact at many or most of the proposed sites discussed in Section 2.2 and Appendix A. This section discusses the basic noise footprints of some representative STOL vehicles, and presents a thrust cutback maneuver for reducing the noise impact in certain areas.

Profile	Type of noise abatement approach	Glide-slope angle, deg		Type of guidance	Intercept altitude, ft	Distance from runway threshold to glide-slope intersection, ft	
		Upper segment	Lower segment				
A	Single segment	---	-2.65	Single ILS beam	---	-1230	
B		---	-4.5		-1230		
C		---	-4.5		-500		
D		---	-5.0		↓		
E		---	-5.5		↓		
F		---	-6.0		↓		
G	Two segment	-6.0	-2.65	Two ILS beams	400	-1230	
H		↓	↓	↓	250	-1230	
I		↓	↓	Single ILS beam curved transition	400	-1130	
J		↓	↓	↓	250	-1110	
K	Deceleration	---	-2.65	Single ILS beam	---	-1230	
L		---	-4.0		↓	---	↓
M		-5.0	-2.65		Two ILS beams	500	
N		-5.0	-2.65		↓	800	

Table 3.2-2 Approach Profiles for Noise Abatement (Ref. 9)

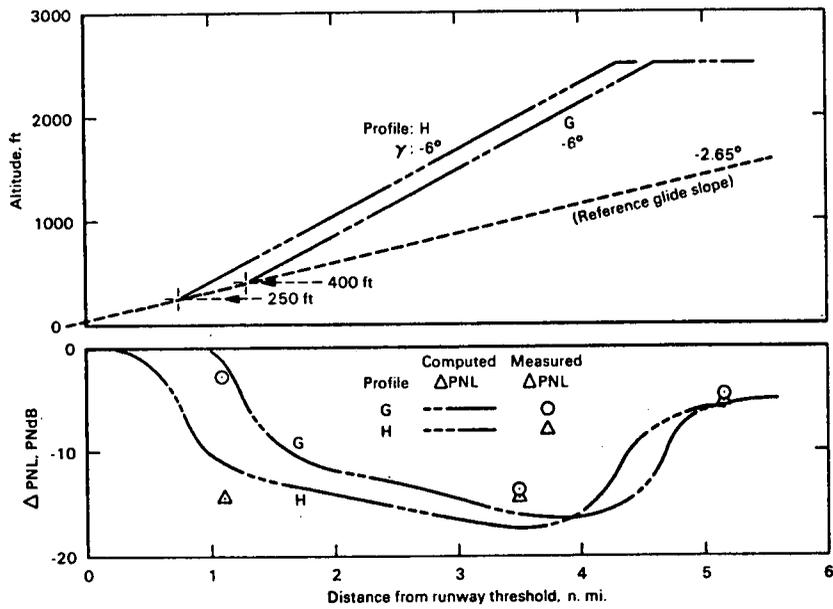
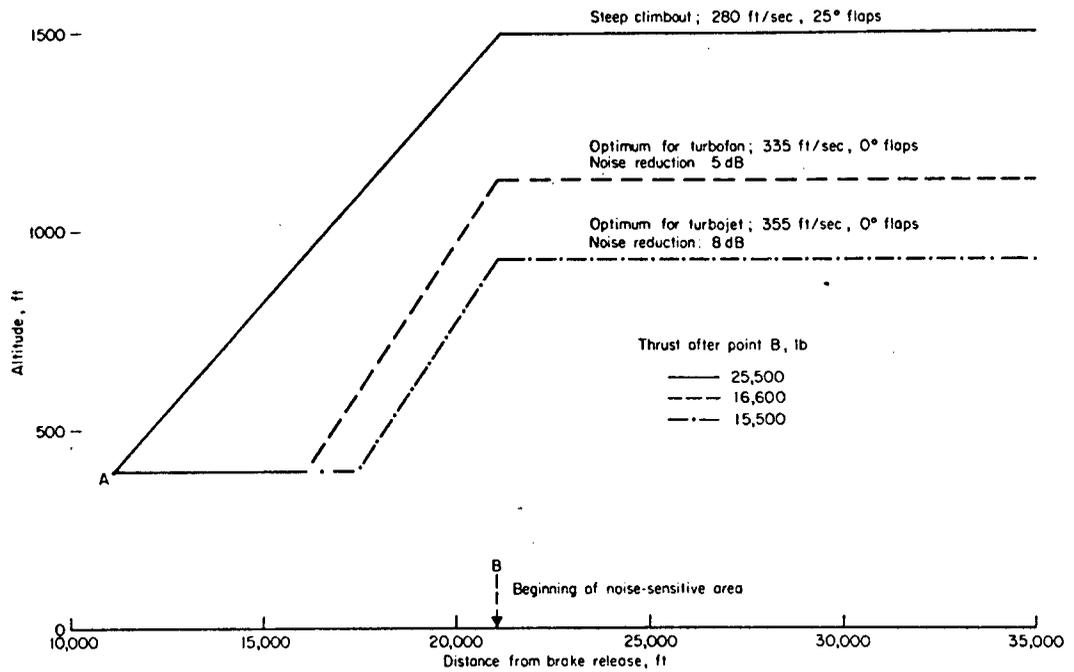


Figure 3.2-6 Noise Reduction with 250- and 400-Foot Intercept Altitudes (Ref. 9)



Note: GTOW = 280,000 lb, T O thrust: 14,000 lb/engine, turbofan or turbojet

Figure 3.2-7 Noise Optimum Flight Paths for Turbojet and Turbofan Aircraft (Ref. 10)

3.2.3.1 Single-Segment Flight Paths

Figures 3.2-8 through 3.2-12 show the basic PNL footprints for two STOL vehicles; the first, having a $PNL_o = 95$ at 500 feet, shall be designated PNL95; the second, with a $PNL_o = 100$ at 500 feet, shall be designated PNL100. The PNL_o 's are assumed to be measured at takeoff thrust levels. To represent vehicles of varying capability or loading, climb angles of 15, 12 and 10 deg are shown, each assuming full takeoff thrust. The approach angles chosen were -7.5 and -9 deg; the former because there seems to be a general consensus in the literature that this would be a good slope, and the latter because it is steeper and quieter than -7.5 deg, while remaining within the pilot-expressed rate-of-descent limit of 1,000 ft/min for a 60-knot approach speed. The thrust level on approach was assumed to be half of the takeoff thrust level. At an approach speed of 60 knots, the rate of descent for the two glide slopes is 790 and 950 ft/min respectively.

The noise generation model, as discussed in Appendix B, is spherical, with no correction for near-ground attenuation or vehicle acceleration. The equation relating PNL to PNL_o at a distance R or a thrust ratio T/T_{max} is given by

$$PNL = 105.76 + 25 \log(T/T_{max}) - [22.1 \log(R/200) + \beta (R/200 - 1) - 1] \quad (3.2-5)$$

where

$$\beta = 0.2(1.069 + 2.157 \sqrt[3]{T/T_{max}})$$

With this model, halving the thrust produces a somewhat greater reduction in PNL than doubling the distance (within about 1,000 feet of the aircraft).

Figures 3.2-8 and -9 show the footprints for takeoff and approach for the PNL95 vehicle; Figs. 3.2-10 and -11 show the same footprints for the PNL100 vehicle. For comparison with present day operations, Fig. 3.2-12 shows a representative takeoff footprint for a present-day turbofan aircraft. (Note the change of scale between the two figures!) The area enclosed by the 95-PNdB contour of a PNL95-type STOL on a 10-deg climbout is only about 1.5% of the comparable CTOL contour area.

Some interesting relationships can be observed from these noise footprints. First, for either the PNL95 or PNL100 vehicles the distance along the runway centerline to a given contour level is about 50% greater with a 10-deg climbout than with a 15-deg climbout. This same ratio holds for the area enclosed by the contour. Second, the distance along the runway centerline to the 95-PNdB contour for the PNL100 vehicle is about 50% greater than for the PNL95 vehicle, while the enclosed area is about 2.4 times as great! Third, if one had to make a choice

between a PNL100-type vehicle that could climb at $\gamma = 15$ deg, and a PNL95-type vehicle that could only climb at $\gamma = 10$ deg, it appears that for noise reasons the PNL95 vehicle might be more acceptable, as its centerline distance to the 95-PNdB contour is about the same as for the PNL100 vehicle, but the sideline distance, and hence the area, is about 37% smaller. Of course the importance of this reduction depends on the site and the STOLport configuration. In some cases it may be more important to reduce the distance along the runway centerline than the sideline distance. In this case either vehicle would be acceptable.

These curves allow one to estimate the length of ground track or area along the runway centerline that would lie within a given PNdB contour. Figure 3.2-13 illustrates this procedure for the PNL95 vehicle, assuming a 1,000-foot takeoff roll. For a 15-deg climb at full power and 7.5-deg approach at half power, the 95-PNdB contour extends almost 5,000 feet along the runway centerline. The curves of Fig. 3.2-14 and Fig. 3.2-15 show the distances from the takeoff or touchdown point as a function of maximum PNL.

Figure 3.2-16 shows what happens to the 95-PNdB contour when the PNL95 vehicle takes off and climbs using a thrust level lower than the normal takeoff thrust. Here it was assumed that one half the normal takeoff thrust could produce a flight path angle about one third as large as the full thrust value.* The results are interesting in that the area enclosed by the reduced-thrust 95-PNdB contour is less than the corresponding area for full thrust, but the distance along the runway centerline to the contour boundary is almost 50% greater.

Of course for this kind of takeoff, safety considerations relative to an engine-out failure, such as reduced climb gradient and/or altitude transient, may outweigh the noise considerations. This could take the form of a minimum altitude required before a thrust cutback could be employed.

Before proceeding to examine other operational procedures that can reduce or reshape the noise footprints, it is useful to look at the relation between Effective Perceived Noise Level (EPNL) and PNL, as EPNL is the basis of the Noise Exposure Forecast (NEF) performance measure discussed earlier. In order to convert the PNL at a point to an NEF value, one must first obtain the EPNL for a particular overflight (i.e., correct the maximum PNL for duration and for pure tones).

For this example we will ignore the pure tone correction, as it is very dependent on the particular engine design, and is simply an add-on factor of a few dB anyway. Also the new high-bypass-ratio fan jets may have reduced tonal energy due to reduced fan tip speeds.

* This approximate relationship was obtained from the performance envelope of the MDC-188 (Ref. 12, p 32, Fig. 10).

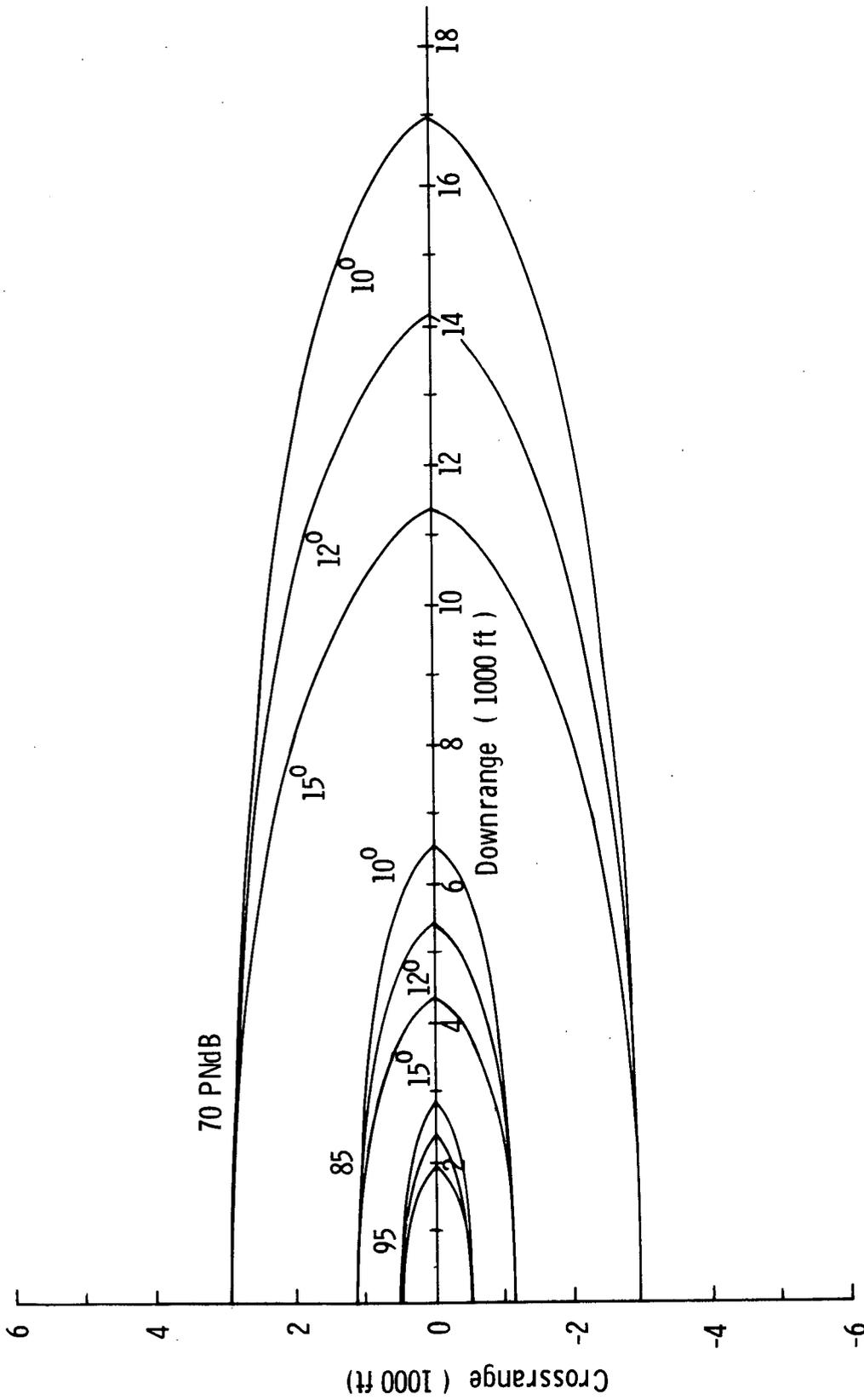


Figure 3.2-8 Takeoff Noise Contours for 15-, 12-, and 10-Deg Flight Path Angles (PNL95 Vehicle)

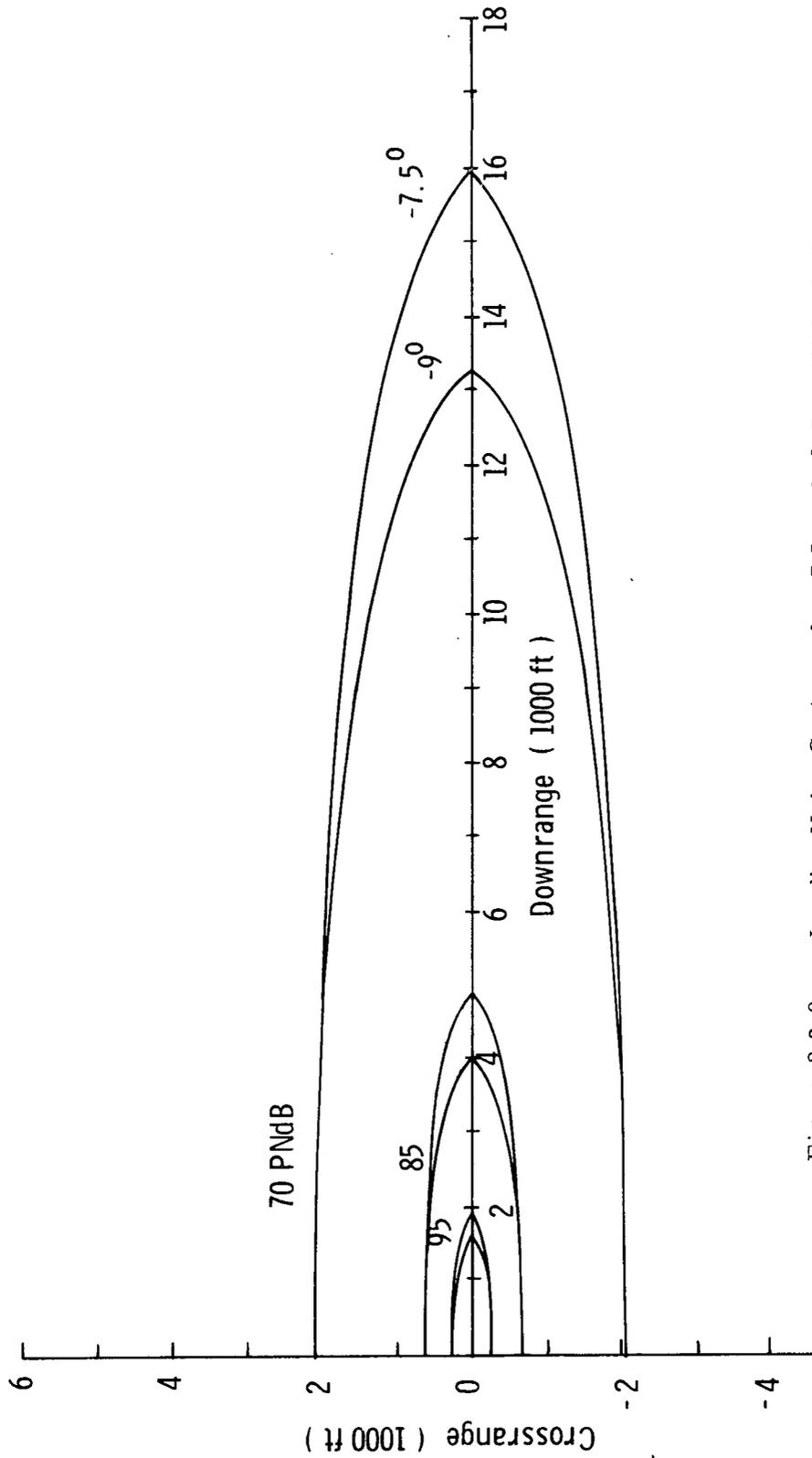


Figure 3.2-9 Landing Noise Contours for -7.5- and -9-Deg Flight Path Angles (PNL95 Vehicle; 50% of Takeoff Thrust)

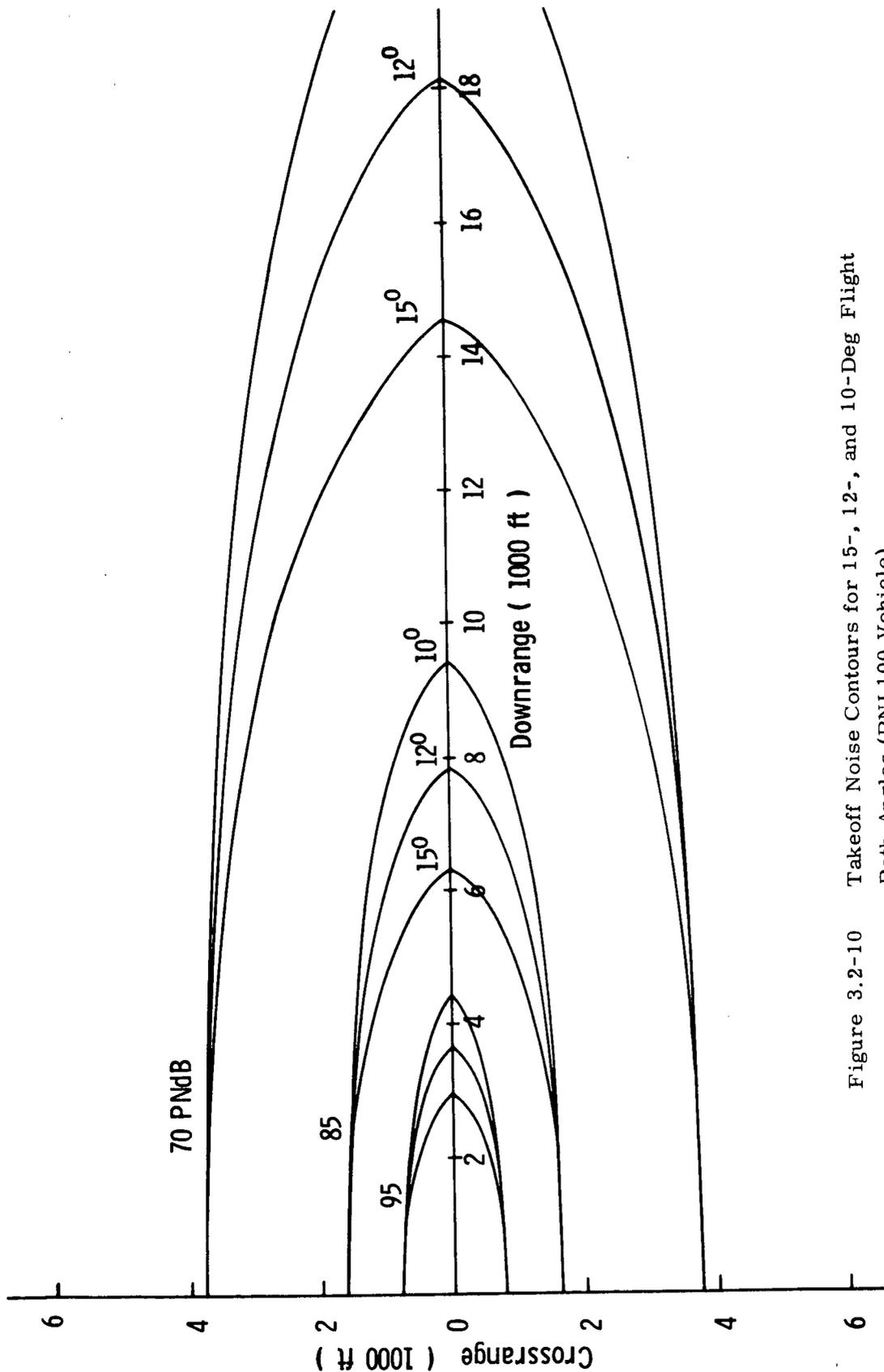


Figure 3.2-10 Takeoff Noise Contours for 15-, 12-, and 10-Deg Flight Path Angles (PNL100 Vehicle)

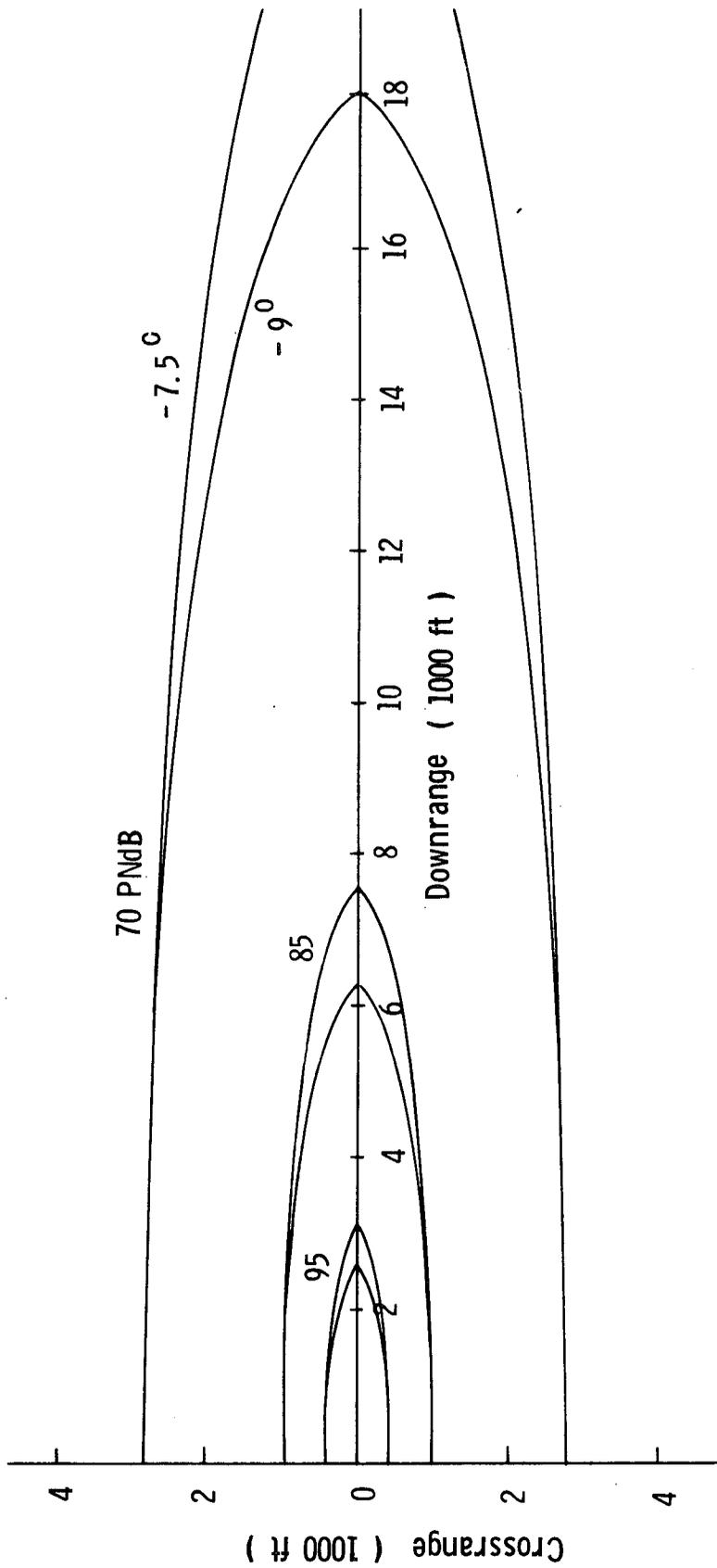


Figure 3.2-11 Landing Noise Contours for -7.5- and -9-Deg Flight Path
Angles (PNL100 Vehicle; 50% of Takeoff Thrust)

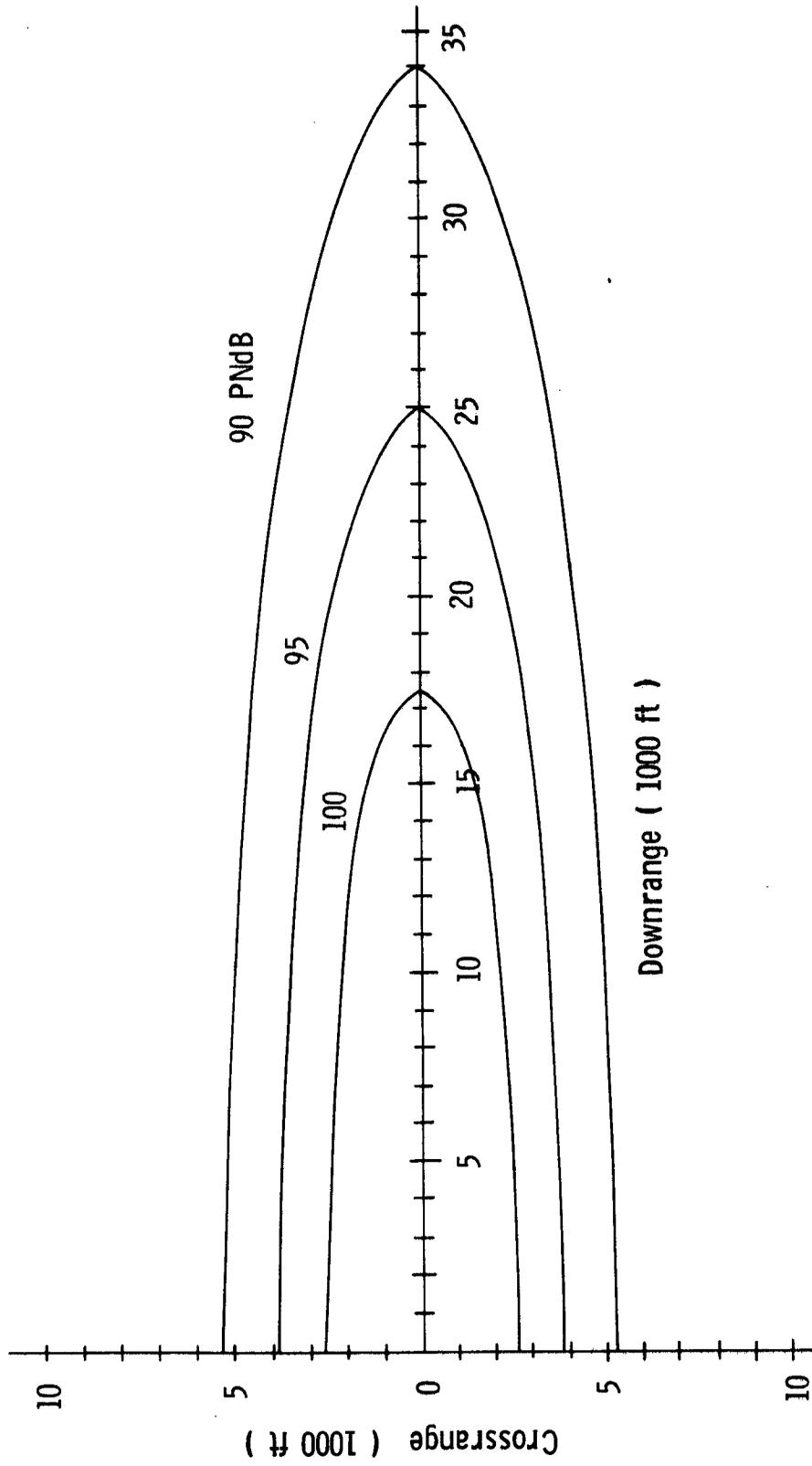


Figure 3.2-12 Representative PNL Contours for Conventional Civil Turbofan Aircraft on Takeoff

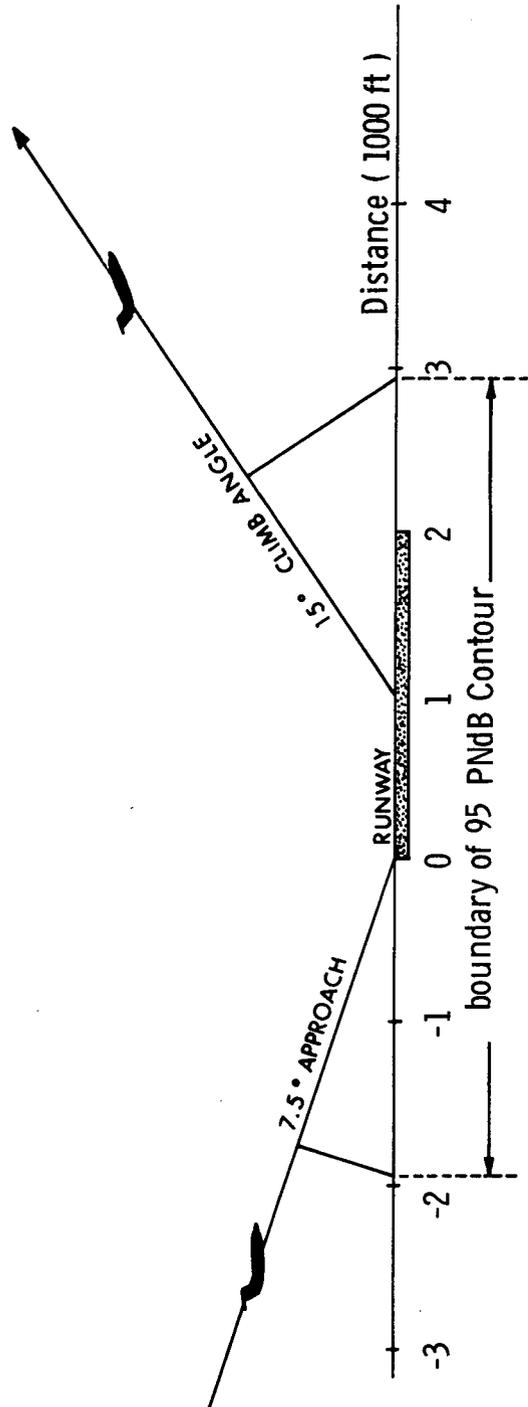


Figure 3.2-13 Limits of 95-PNdB Contour for PNL95 Vehicle

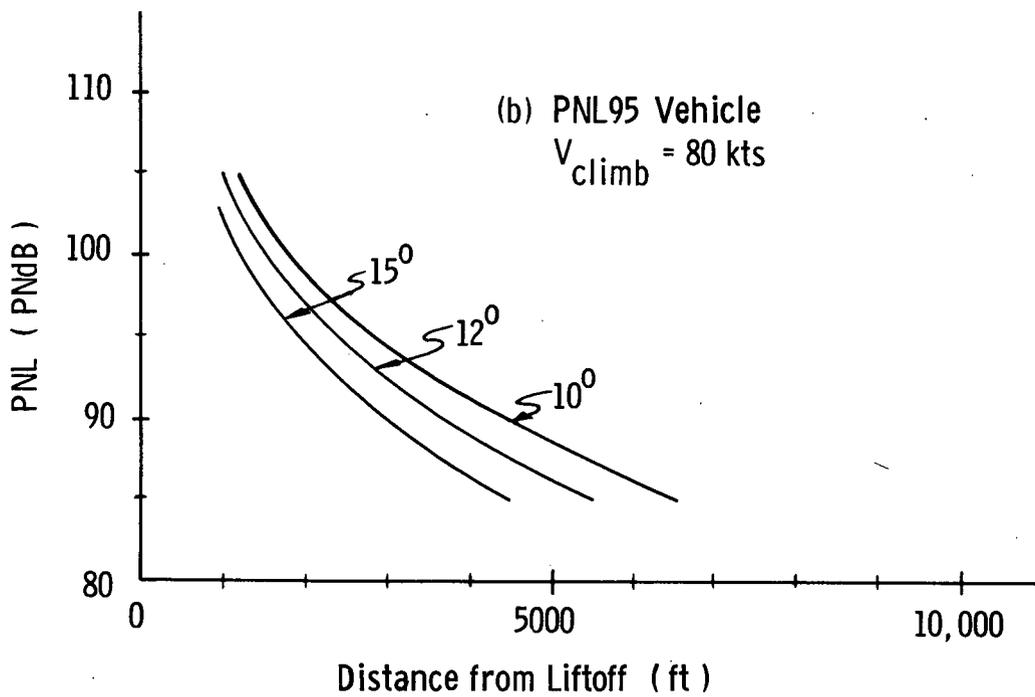
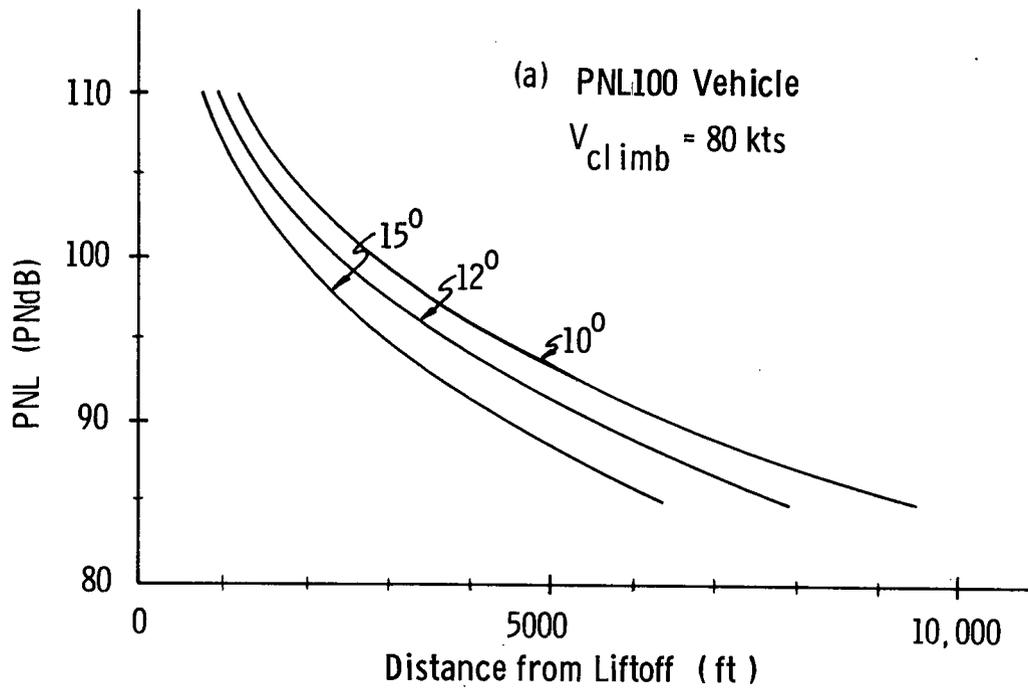


Figure 3.2-14 Maximum Noise Level as a Function of Distance from the Point of Liftoff

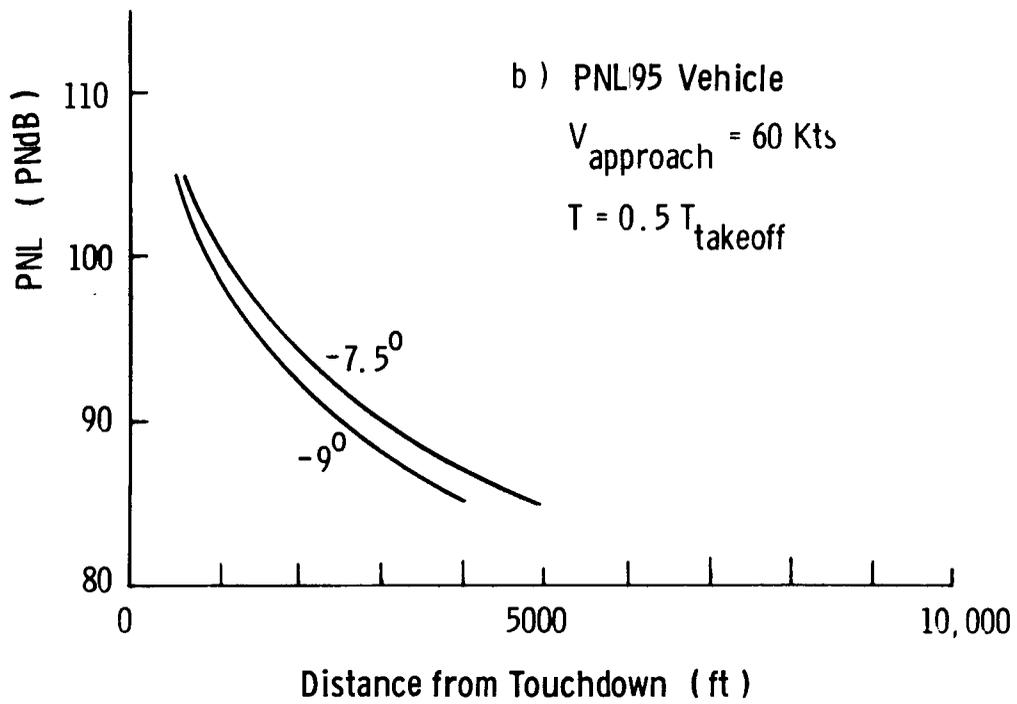
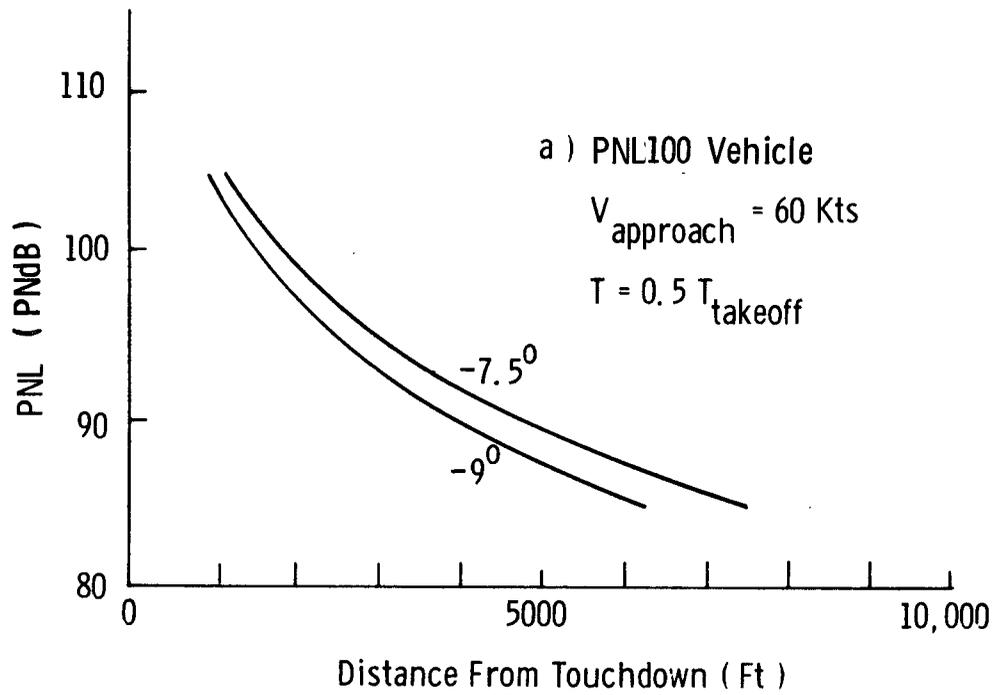


Figure 3.2-15 Maximum Noise Level as a Function of Distance from the Point of Touchdown

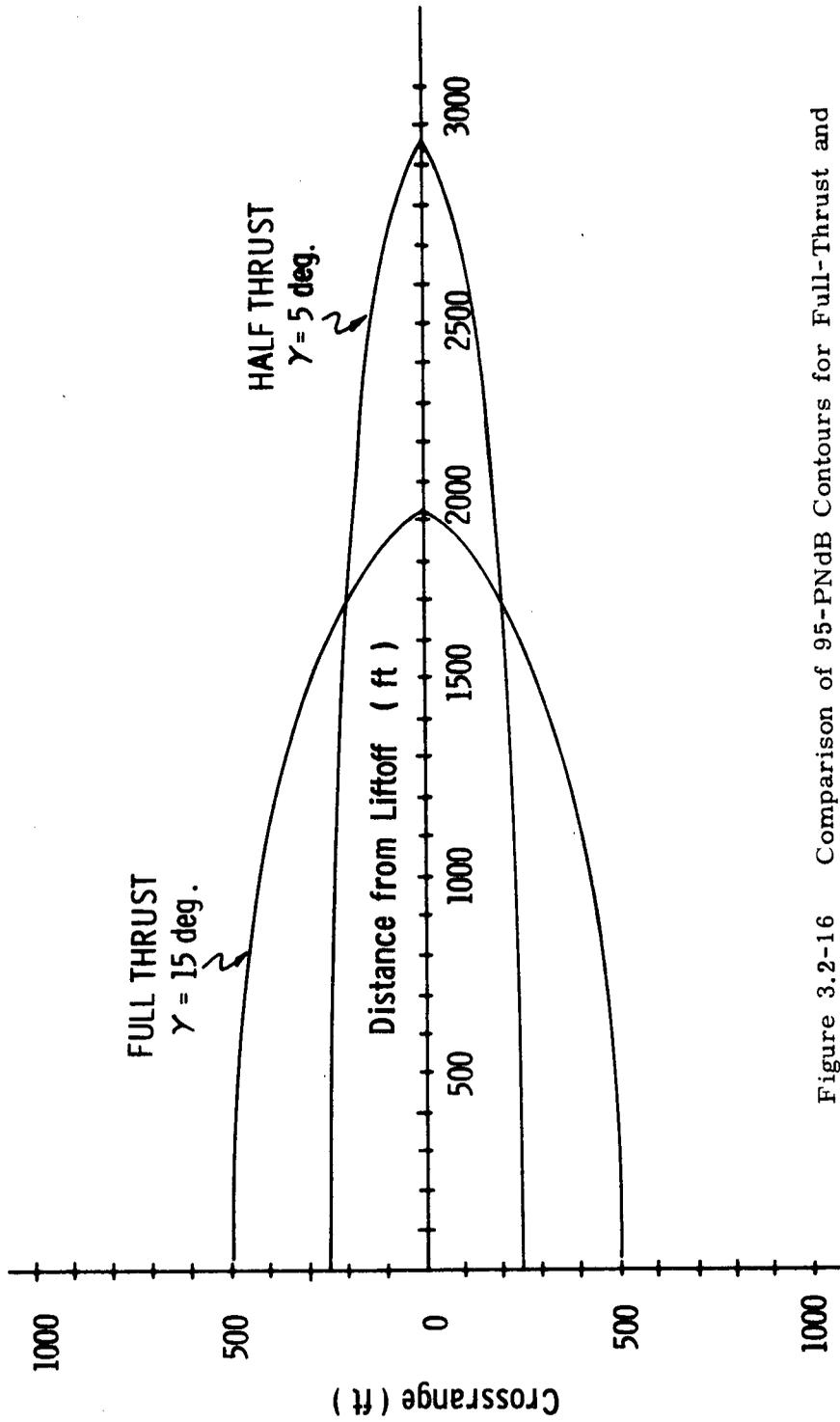


Figure 3.2-16 Comparison of 95-PNdB Contours for Full-Thrust and Half-Thrust Takeoffs (PNL95 Vehicle)

The duration correction can be computed by using Eq. 3.2-4; thus

$$EPNL = PNL_{\max} + \Delta PNL_{DUR} \quad (3.2.-6)$$

Table 3.2-3 gives the duration correction factors for the takeoff and approach cases discussed above, and Fig. 3.2-17 shows the effect of the correction factor by plotting EPNL vs PNL.

For the simplifying assumptions used in this analysis (spherical noise model, no near-ground attenuation factor, no tonal concentrations, etc.) the duration correction for a listener on a particular contour depends only on PNL_0 and velocity, not on flight path angle or location on the contour. This means that the EPNL contours have the same shape as the PNL contours (i.e., parabolic). From Fig. 3.2-17 it is seen that for the PNL95 vehicle on an 80-knot climbout, the EPNL and PNL contours are identical at about the 90-PNdB level, as the duration correction is zero there. For the PNL100 vehicle, the contours are equivalent at about the 95-PNdB level. Figure 3.2-18 shows the EPNL contours for 95, 90, and 85 EPNdB, which can be compared with the PNL contours of Figs. 3.2-8 through -12.

The NEF value now depends only on the number of flights during the day or night (see Eq. 3.2-1). For an example relating PNL to NEF, assume a flight frequency of 100/day. Table 3.2-4 gives the NEF values for several values of PNL. Referring back to Fig. 3.2-14, the 95-PNdB contours would become NEF = 25.6 for takeoff, and NEF = 24.0 for approach.

Figure 3.2-19 shows the NEF 30 contours for the PNL95 and PNL100 vehicles for a 15-deg, 80-knot climbout and -7.5-deg, 60-knot approach.

3.2.3.2 Two-Segment Flight Paths

Having seen the basic PNL, EPNL, and NEF contours for the single-segment flight paths, it is useful to look at the improvements made possible by using two-segment flight paths.

On takeoff the flight path consists of an initial segment at maximum flight path angle, followed by a second segment at reduced thrust and lower climb gradient. The point at which the thrust cutback occurs is determined by the particular PNL contour that is to be reduced.

What is desired is to find the minimum distance d from the liftoff point along the runway centerline at which a given PNL will not be exceeded. For a listener at any such point, the vehicle will start its climbout at full thrust and maximum flight path angle. As the vehicle approaches the listener, and the specified maximum

PNL	Duration Correction Δ PNL	
	PNL95 Vehicle	PNL100 Vehicle
105	- 6.9 PNdB	- 4.8 PNdB
100	- 4.8	- 2.8
95	- 3.0	- 1.1
90	- 1.1	+ 0.8
85	+ 0.8	+ 2.4

a) Landing (60 kts, 50% of Takeoff Thrust)

PNL	Duration Correction Δ PNL	
	PNL95 Vehicle	PNL100 Vehicle
105	- 5.1 PNdB	- 3.4 PNdB
100	- 3.3	- 1.6
95	- 1.6	0.0
90	+ 0.02	+ 1.4
85	+ 1.5	+ 2.6

b) Takeoff (80 kts, Full Thrust)

Table 3.2-3 Duration Correction for STOL Takeoff and Landing

PNL	PNL95 Vehicle				PNL100 Vehicle			
	Climb (V=80kts)		Approach (V=60kts)		Climb (V=80kts)		Approach (V=60kts)	
	EPNL	NEF	EPNL	NEF	EPNL	NEF	EPNL	NEF
105	100.0	31.4	97.8	29.8	101.7	33.6	100.0	32.0
100	96.7	28.8	95.4	27.4	98.5	30.8	97.2	29.2
95	93.5	25.7	92.1	24.2	95.1	27.2	93.9	25.9
90	90.1	22.2	89.0	20.9	91.4	23.5	90.8	22.8
85	86.5	18.5	85.8	17.8	87.6	19.6	87.4	19.4

Table 3.2-4 Conversion of PNL to NEF, assuming 100 flights/day
(No correction for Pure Tones)

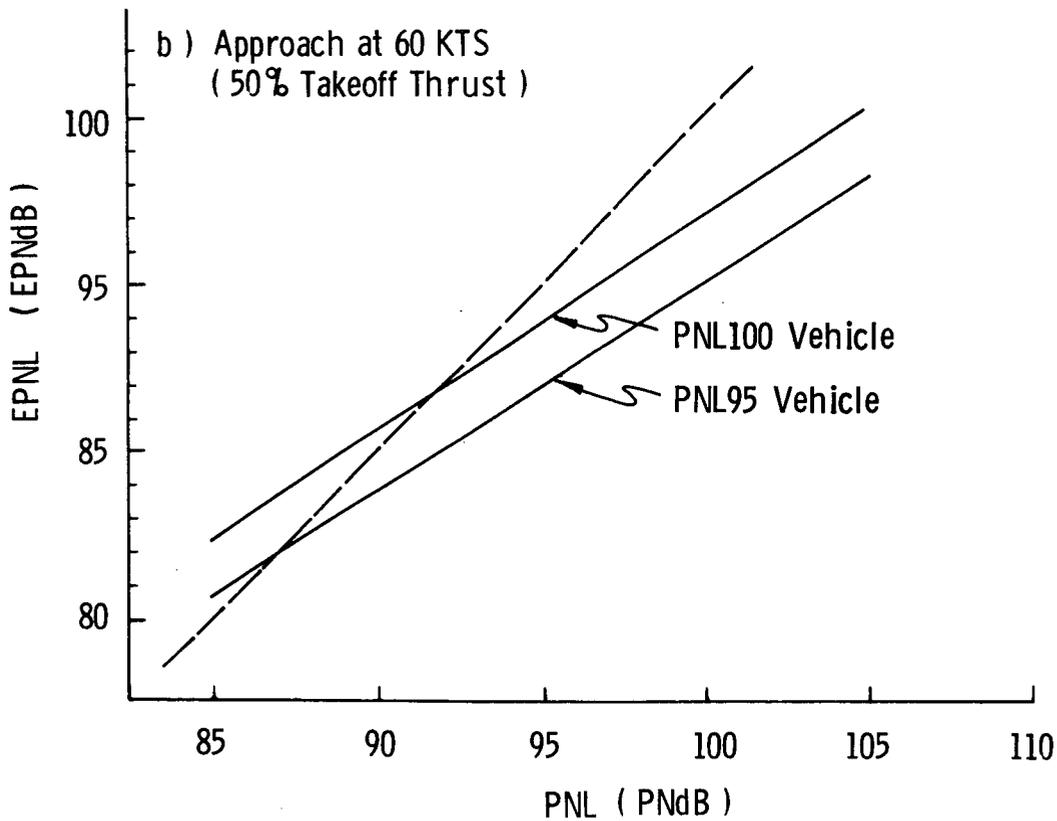
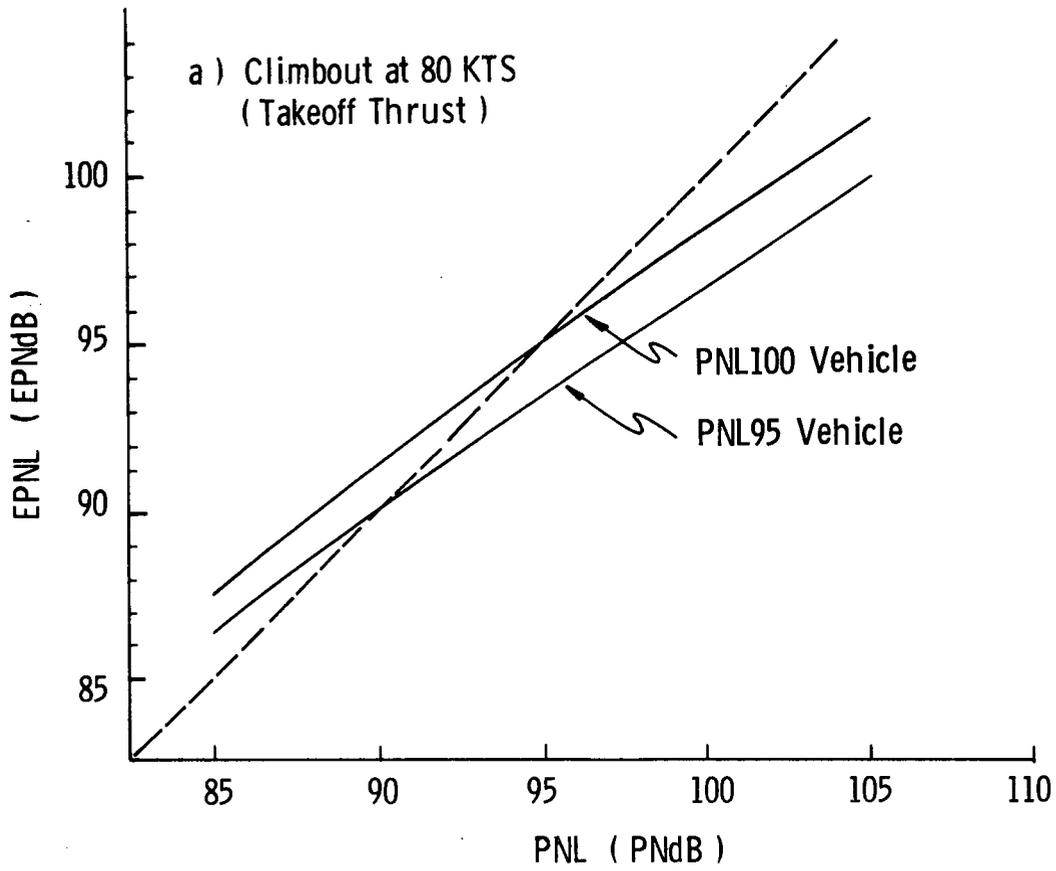
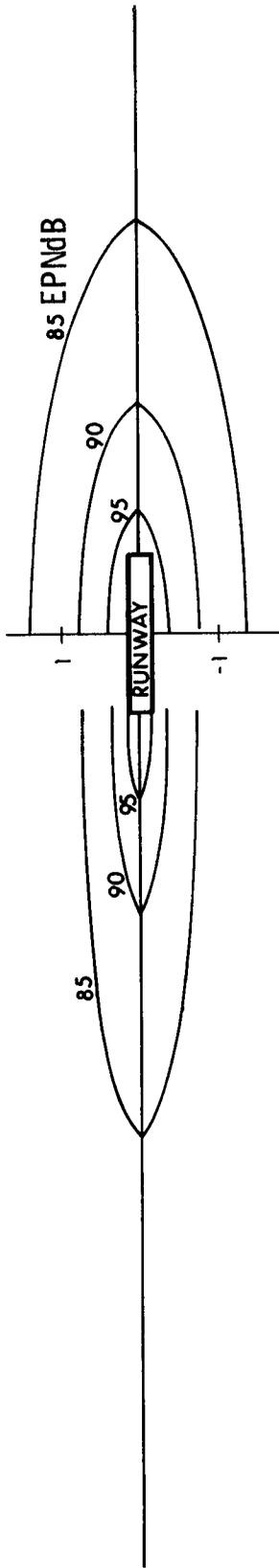
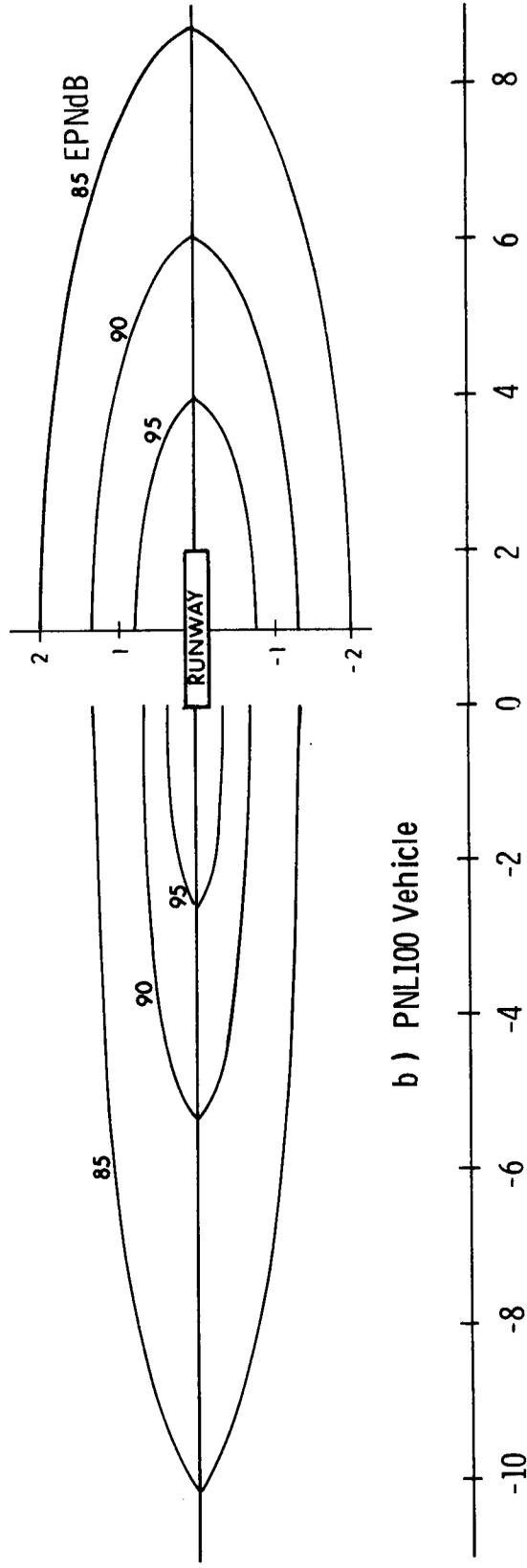


Figure 3.2-17 EPNL vs PNL for Takeoff and Approach (Duration Correction Only; No Correction for Pure Tones)



a) PNL95 Vehicle



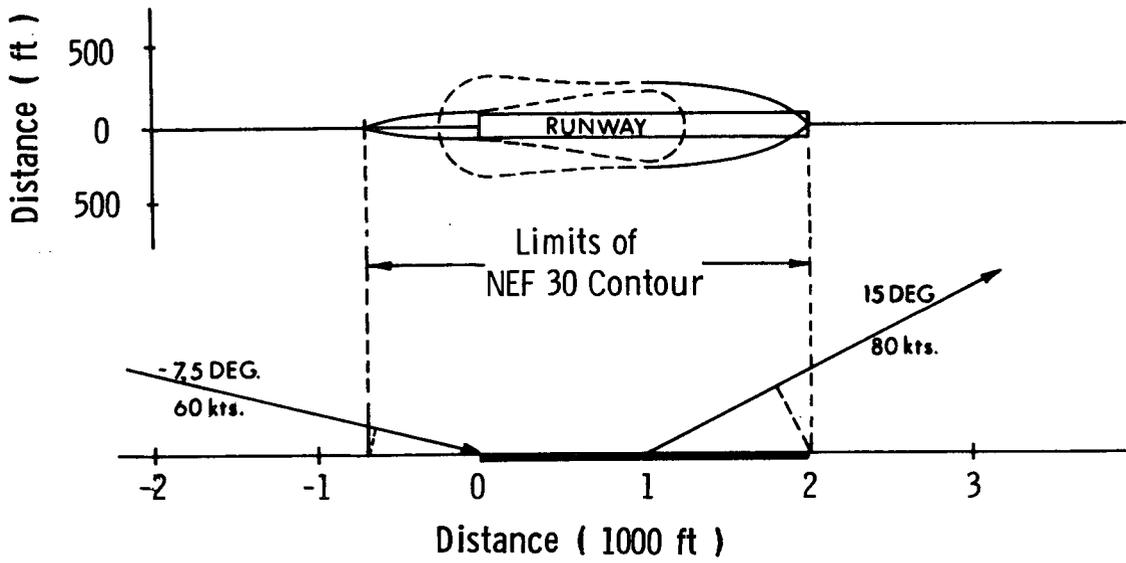
b) PNL100 Vehicle

Distance (1000 ft)

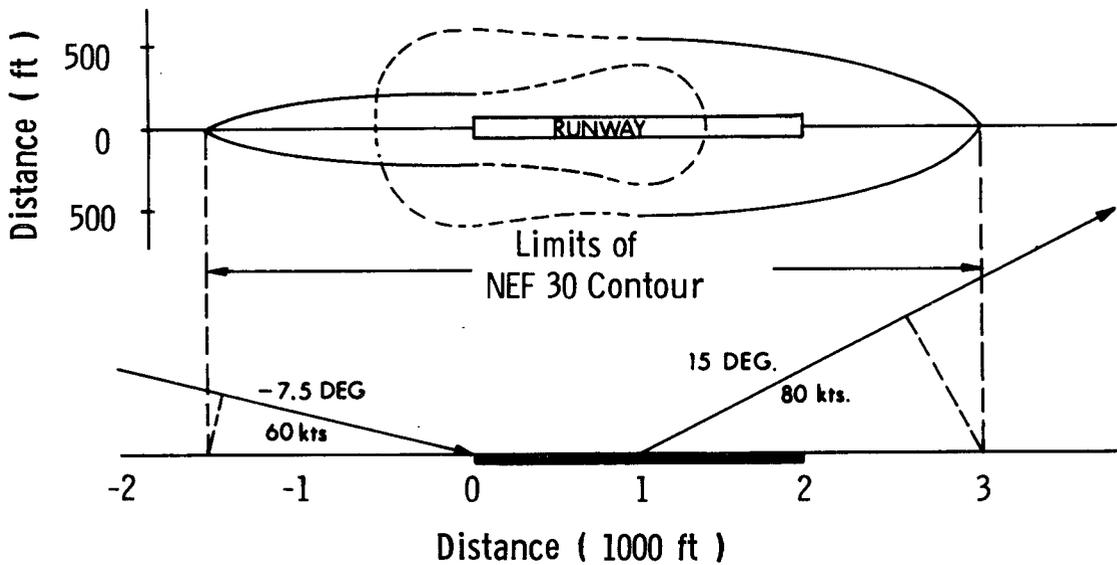
Figure 3.2-18 EPNL Contours for Approach and Takeoff (Approach: $\gamma = -7.5$ Deg,

V = 60 Knots; Takeoff: $\gamma = 15$ Deg, V = 80 Knots)

C.2



a) PNL95 Vehicle



b) PNL100 Vehicle

Figure 3.2-19 NEF 30 Contours for Approach and Takeoff Assuming 100 Operations/Day (Approach: $\gamma = -7.5$ Deg, $V = 60$ Knots; Takeoff: $\gamma = 15$ Deg, $V = 80$ Knots)

PNL is reached, a thrust cutback of 50% is performed, and the vehicle continues to climb at 1/3 the initial flight path angle.¹² The PNL, which decreases when the thrust is reduced, increases again and reaches the specified maximum level as the vehicle passes over the listener. The PNL then decreases as the vehicle continues its reduced-thrust climb.

Thus to find the distance d at which a given PNL will not be exceeded, one need only compute the two distances R_1 and R_2 that give the desired PNL_{max} for full and half thrust, and then use the appropriate trigonometric relationships to solve for d , x , and h . The geometry of the problem is illustrated in Fig. 3.2-20.

The PNL contours for the PNL95 and PNL100 vehicles on an initial climb angle of 15 deg are shown in Figs. 3.2-21 and -22. In Fig. 3.2-21(a), the thrust cutback point was selected to reduce the 95-PNdB contour for the PNL95 vehicle. With the thrust cutback occurring at a downrange distance (from liftoff) of 777 feet and an altitude of 208 feet, a listener 1,232 feet downrange would receive a maximum PNL of 95. Compared with a downrange distance of 1,932 feet without a thrust cutback, a 700-foot (36%) reduction in distance is achieved. However, while the 95-PNdB contour is reduced, the 85-PNdB contour is extended by over 1,000 feet because the climb angle is reduced after the thrust cutback. If the thrust cutback is timed to reduce the 85-PNdB contour, as shown in Fig. 3.2-21(b), about a 1,400-foot (32%) decrement can be achieved. In this case the cutback occurs at a downrange distance from liftoff of about 2,000 feet and an altitude of 535 feet. From the figure it is apparent that the 95-PNdB contour is not affected by this maneuver. Figure 3.2-22 shows that similar results are obtained for the PNL100 vehicle.

The values of x , h , and the minimum distance d are given in Table 3.2-5 as functions of the maximum allowable PNL. The initial flight path angles are 15, 12, and 10 deg as in the single-segment case. It is evident that the thrust cutback results in significant reductions in distance-from-liftoff for a given PNL (about 700 feet for the 95-PNdB contour). No attempt has been made to optimize the climb profile, so that further improvements might be possible with other profiles. Also the assumption that 50% thrust produces a 66% reduction in flight path angle is only approximate — the actual relationship would have to be determined for a specific vehicle.

Looking further at the contours, one observes that these maneuvers produce only moderate changes in PNL. In Fig. 3.2-21(a), even though the 95-PNdB contour is moved in 700 feet, a listener at point A would only experience a reduction in PNL from 95 to about 93 PNdB, which might not even be noticeable. A listener at point B, however, would experience a 5-PNdB reduction from 100 to 95 PNdB. A listener at point C would be unaffected (i.e., the 90-PNdB contour crosses there with or without the cutback) while the listener at point D would have his PNL increased

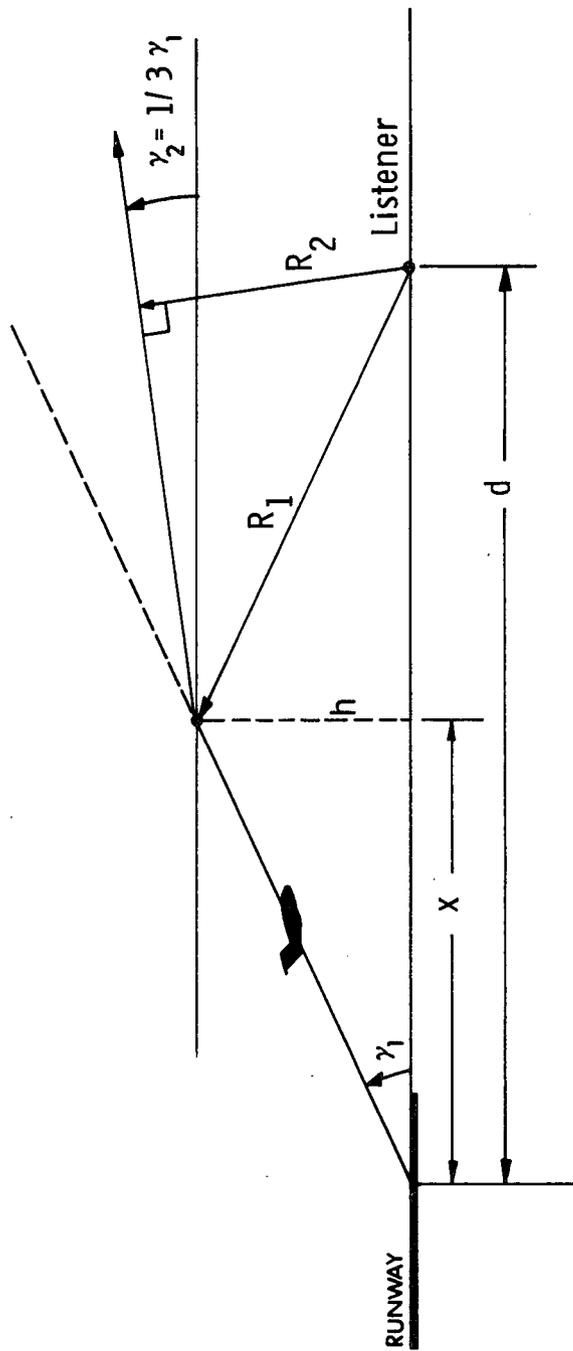


Figure 3.2-20 Two-Segment Glide Slope Geometry

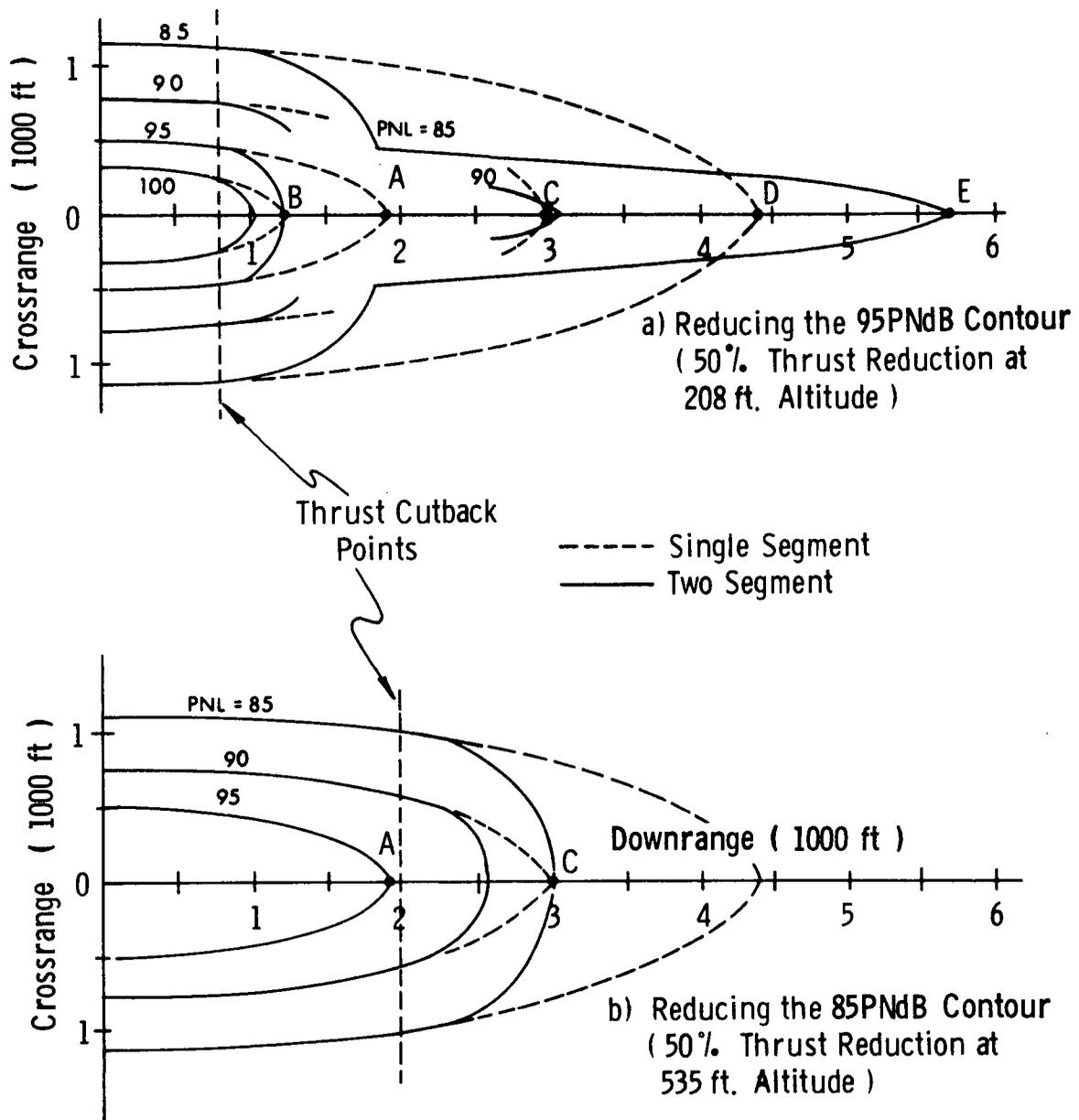


Figure 3.2-21 Comparison of PNL Contours for Single-Segment and Two-Segment Climbouts (PNL95 Vehicle; $\gamma_1 = 15$ Deg, $\gamma_2 = 5$ Deg)

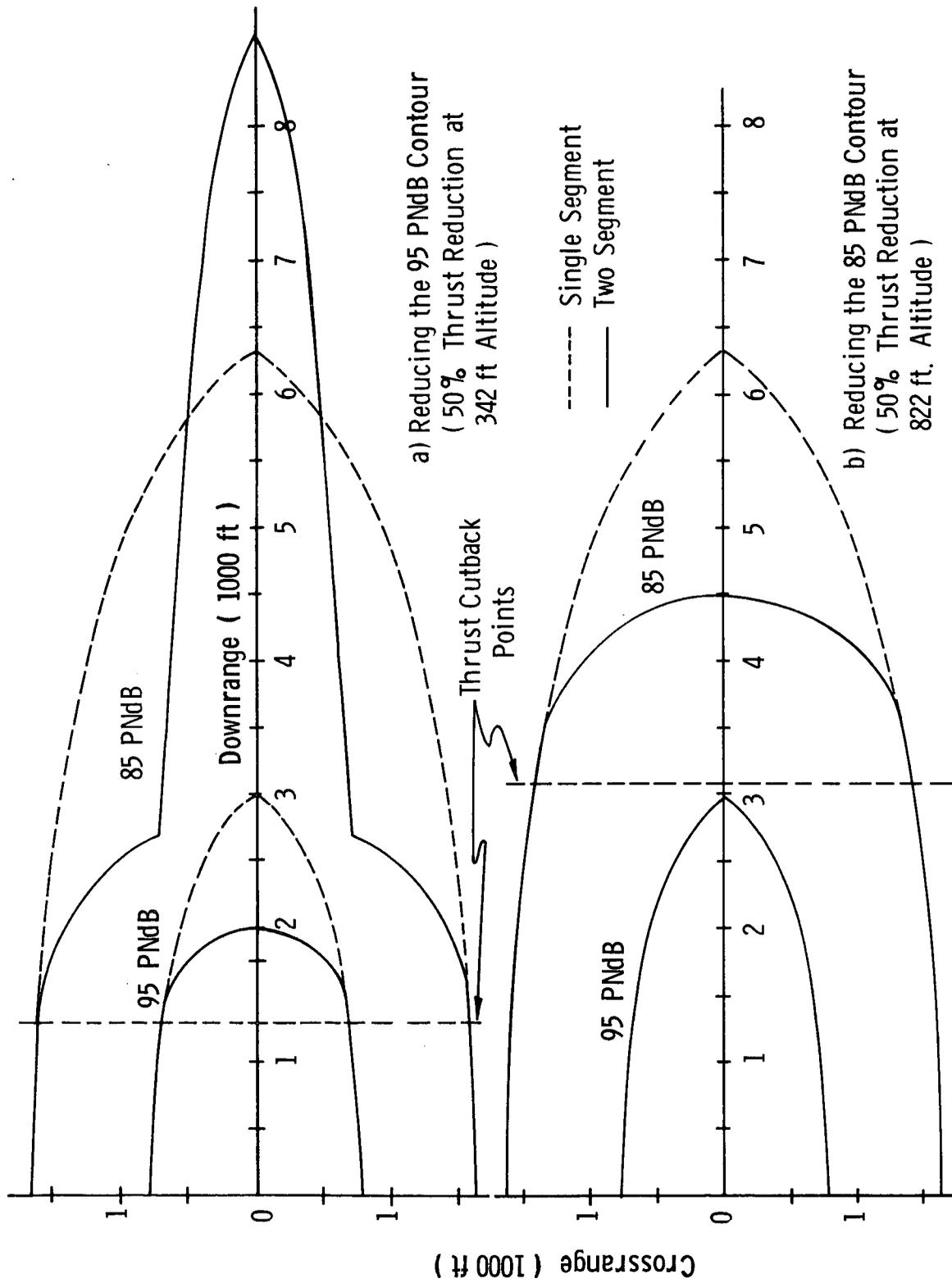


Figure 3.2-22 Comparison of PNL Contours for Single-Segment and Two-Segment Climbouts (PNL100 Vehicle; $\gamma_1 = 15$ Deg, $\gamma_2 = 5$ Deg)

PNL	PNL95 Vehicle									PNL100 Vehicle								
	$\gamma = 15 \text{ deg}$			$\gamma = 12 \text{ deg}$			$\gamma = 10 \text{ deg}$			$\gamma = 15 \text{ deg}$			$\gamma = 12 \text{ deg}$			$\gamma = 10 \text{ deg}$		
	d	h	x	d	h	x	d	h	x	d	h	x	d	h	x	d	h	x
105	468	77	288	557	81	379	646	83	468	766	128	478	912	133	626	1058	136	774
100	767	128	478	912	133	626	1058	136	773	1232	208	776	1468	216	1016	1704	221	1255
95	1231	208	776	1467	216	1016	1704	221	1255	1958	342	1275	2340	354	1664	2722	362	2050
90	1958	342	1275	2340	354	1664	2722	362	2050	3004	535	1997	3598	552	2600	4191	564	3200
85	3004	535	1997	3598	553	2600	4191	564	3200	4487	822	3068	5388	847	3984	6289	863	4895

Table 3.2-5 Distance of PNL Contour Limits From Takeoff Point
for Two-Segment Climb Profiles

by a couple of PNdB. In Fig. 3.2-21(b), the listener at A is unaffected, but the listener at C experiences a 5-PNdB reduction from 90 to 85 PNdB.

From these figures it appears that if there is a small, particularly sensitive area close in to the STOLport, such as a group of houses, a school, a hospital or a concert hall, a thrust cutback can provide some reduction in annoyance. The maneuver of Fig. 3.2-21(b) would produce a barely-perceptible reduction in PNL (3-5 PNdB) over about a 2,000-foot range from approximately 2,500 feet to 4,500 feet from the liftoff point. If the thrust cutback is performed earlier (e.g., Fig. 3.2-21(a)) the range over which a perceptible reduction in PNL occurs is smaller — about 1,000 feet in this example. As the basic vehicle noise increases the thrust cutback becomes more meaningful, as larger areas can share in the PNL reduction.

On landing approach, noise reduction procedures may be limited due to piloting constraints — such as (1) a reluctance to exceed a rate of descent greater than about 1,000 ft/min close to the ground, and (2) a desire to be aligned with the runway and on the final approach slope when breaking out of the clouds at 200 feet in Category I weather conditions. The times between breakout and touchdown for approach slopes of -7.5 and -9 deg are about 15 and 12.5 sec respectively for an approach speed of 60 knots. This compares with about 20 sec for a CTOL aircraft on a 120-knot, -3-deg approach. The acceptability of reducing the final approach segment will depend on the performance and reliability of the avionics systems, and perhaps the crosswind component and/or turbulence level. An analysis of the type shown in Section 3.4, extended to include vehicle dynamics, wind effects, and pilot performance, would be very useful in helping to determine approach profiles. It is apparent from Fig. 3.2-19, however, that if NEF 30 is the guideline for noise acceptability, then approach maneuvering will probably not lead to very significant NEF changes for a PNL95-type vehicle, simply because the NEF 30 contour is quite small.

3.2.3.3 Conclusions and Recommendations

A preliminary look was taken at some representative STOL noise footprints, and some operational procedures that might reduce or reshape the noise impact. For a representative vehicle with a basic full-throttle PNL of 95 PNdB at 500 feet, the 95-PNdB contours for approach and takeoff cover a runway centerline distance of about 5,000 feet, assuming a 1,000-foot takeoff and landing roll (Fig. 3.2-14). This means that a STOL could operate from a conventional jet runway and keep the 95-PNdB contour from exceeding the ends of the runway. This is in contrast to the 95-PNdB contours of conventional jet aircraft, which can extend out 5 miles from the runway (Fig. 3.2-12).

If the Noise Exposure Forecast is used as the noise measure, the NEF 30 contour for the same vehicle (including both approach and takeoff) spans less than 3,000 feet along the runway centerline. For a 2,000-foot STOL runway, much of the area under the NEF 30 contour lies on the runway (Fig. 3.2-19).

Operations at a separate STOLport, where there may be noise sensitive areas close to the runway, may be quieted by a thrust cutback during climbout. For the representative PNL95 vehicle, cutting the thrust in half at an altitude of 200 feet produces a moderate (3-5 PNdB) reduction in PNL over a 1,000 foot segment along the runway centerline (from about 1,100-2,100 feet from liftoff - Fig. 3.2-21). The thrust cutback can be timed to reduce the noise over any particular area, but if there are altitude restrictions on performing the cutback, due to safety considerations, it may not be possible to reduce the 95-PNdB contour. Even so, if the noise sensitive areas are located 2,000 feet or more from the end of a STOL runway, their PNL should not exceed 95 PNdB, and a thrust cutback at a more reasonable altitude, say 500 feet, could produce a 3-5 PNdB reduction over that area.

This analysis represents a first step toward the understanding of possible noise abatement operational procedures. The work should be extended by including (1) calculation of the EPNdB and NEF contours for the two-segment climbouts; (2) selection of three-dimensional flight paths, with and without thrust cutbacks; (3) more detailed examination of performance envelopes and vehicle dynamics to find the most desirable operating procedures and (4) corroboration of the engine noise model with data from the new quiet engines under development.

3.2.4 Optimum Noise-Abatement Trajectories

The work of this section models a particular STOL aircraft (a jet powered augmentor-wing vehicle) in detail and applies a steepest-descent numerical optimization procedure to minimize an annoyance performance index. The approach uses four state variables with ten listeners for the two-dimensional problem considered.* The program may easily be extended to three dimensions with an increased number of listeners. The program includes state and control variable inequality constraints and thus greatly increases the realism of the model. Five control variables are modulated within given bounds so that the annoyance function is minimized.

The steepest-descent optimization technique¹⁵ is the simplest of the functional optimization schemes. Its advantages are that (1) it is easy to program, (2) each iteration on the computer is relatively quick, and (3) convergence to the minimizing

*The listeners are located at half-mile intervals along the extended runway centerline in the takeoff direction.

control profile is rapid to within engineering accuracy. Its disadvantage is that it will not converge precisely; consequently, there is always some uncertainty about potential improvement.

3.2.4.1 Performance Index

The functional form of the performance index is

$$PI = \sum_{i=1}^n P_i S_i \left[\int_t^{t+\Delta t_i} \phi_i dt \right] \quad (3.2-7)$$

where the subscript i represents a particular listener of a total of n . The integral $\int \phi_i dt$ is the perceived annoyance, P_i is population density, S_i is the sensitivity of the population to its noise environment, and Δt_i is the interval during which the noise is considered annoying.* The above performance index is based on the hypothesis that annoyance is perceived through a time integration of the total noise environment.

The form of the annoyance function is

$$\int_t^{t+\Delta t} \phi_i dt = K \log \left[\frac{1}{T_0} \int_t^{t+\Delta t_i} 10^{PNL_i/K} dt \right] \quad (3.2-8)$$

where

PNL_i = Perceived Noise Level (PNdB)

T_0 = arbitrary reference time (normally $T_0 = 10$ sec)

K = constant determining duration penalty

PNL_i is a function of thrust, T , and distance from aircraft to listener, Y_i , given as

$$PNL_i = 115 + 25 \log(T/T_{\max}) - [22.1 \log(Y_i/200) + \beta(Y_i/200 - 1) + 1] \quad (3.2-9)$$

* In this analysis, the interval was taken as the time interval from the start of the flight simulation to 5,000-foot altitude.

where

T_{\max} = maximum sea level thrust

β = atmospheric attenuation factor

$$= 0.2(1.069 + 2.157 \sqrt[3]{T/T_{\max}})$$

The assumptions are: (1) that fan noise dominates jet noise, (2) that fan noise is not highly directional, and (3) that there are no tonal concentrations (see Appendix B). Given that noise field prediction techniques are not well developed, the noise model presented above is felt to be a reasonable representation of the noise sources.

3.2.4.2 Equations of Motion

The state variables are altitude, h , downrange, R , velocity magnitude, V , and flight path angle, γ . The control variables are angle of attack, α , angle of incidence (jet engine nozzle deflection), i , primary thrust, T_p , augmentor thrust, T_a^* and flap angle, δ_F .

The equations of motion of a point mass representation of the vehicle are:

$$\dot{h} = V \sin \gamma \quad (3.2-10)$$

$$\dot{R} = V \cos \gamma \quad (3.2-11)$$

$$\dot{V} = qg/(W/S) [C_J \cos(\alpha + i) - C_D] - g \sin \gamma \quad (3.2-12)$$

$$\dot{\gamma} = qg/(VW/S) [C_J \sin(\alpha + i) + C_L] + \left[\frac{V}{R+h} - \frac{g}{V} \cos \gamma \right] \quad (3.2-13)$$

where

$$C_J = T_p/qS; \quad C_{J_a} = T_a/qS$$

$$C_L = C_L(\alpha, C_{J_a}, \delta_F)$$

$$C_D = C_D(\alpha, C_{J_a}, \delta_F)$$

$$q = 1/2 \rho V^2$$

*The augmentor thrust, T_a , does not appear explicitly in the equations of motion, but is included in the lift and drag coefficients.

The air density is ρ , the wing loading of the aircraft is W/S .

In effect two different vehicles were modeled in this study. The first had a thrust of 22,910 pounds and a weight of 40,000 pounds, giving a thrust-to-weight ratio (T/W) of about 0.57. This model was used to compare the effects of fixed flap angle versus variable flap angle. The second vehicle used the same weight but a thrust of 18,600 pounds, hence its T/W was 0.465. Here the flap angle was a control variable, affecting the lift and drag forces. In both cases, however, the primary thrust and augmentor thrust were assumed separately controllable.

For the case of constant flap angle (60 deg) the aerodynamic data was fitted by the following functions:

$$C_L = 2.1 + 0.082\alpha + (0.02\alpha + 2) C_{J_a} + \Delta C_{L(BLC)} \quad (3.2-14)$$

$$C_D = 0.3 - 0.87 C_{J_a} + 0.052 (C_L - 1)^2 \quad (3.2-15)$$

The constant $\Delta C_{L(BLC)}$ is zero if boundary layer control is not included.

When the flap angle is used as a control variable, the lift and drag coefficients are calculated by fitting data points to a polynomial in factored form using a Lagrangian interpolation method from Ref. 17.

$$C_L(\alpha, C_{J_a}, \delta_F) = \sum_{i=0}^2 \sum_{j=0}^3 \sum_{k=0}^3 L_{ijk}(\alpha, C_{J_a}, \delta_F) C_L(\alpha_i, C_{J_{a_j}}, \delta_{F_k}) \quad (3.2-16)$$

$$C_D(\alpha, C_{J_a}, \delta_F) = \sum_{i=0}^2 \sum_{j=0}^3 \sum_{k=0}^3 L_{ijk}(\alpha, C_{J_a}, \delta_F) C_D(\alpha_i, C_{J_{a_j}}, \delta_{F_k}) \quad (3.2-17)$$

where

$$L_{ijk}(\alpha, C_{J_a}, \delta_F) = \frac{\prod_{\ell=0}^2 (\alpha - \alpha_\ell) \prod_{m=0}^3 (C_{J_a} - C_{J_{a_m}}) \prod_{n=0}^3 (\delta_F - \delta_{F_n})}{(\ell \neq i) \quad (m \neq j) \quad (n \neq k)} \quad \frac{\prod_{\ell=0}^2 (\alpha_i - \alpha_\ell) \prod_{m=0}^3 (C_{J_{a_j}} - C_{J_{a_m}}) \prod_{n=0}^3 (\delta_{F_k} - \delta_{F_n})}{(\ell \neq i) \quad (m \neq j) \quad (n \neq k)}$$

The functions L_{ijk} so defined have the necessary property that

$$L_{ijk}(\alpha_\ell, C_{J_{a_m}}, \delta_{F_n}) = \begin{cases} 1 & \text{if } i = \ell, j = m, k = n \\ 0 & \text{otherwise} \end{cases}$$

This method of obtaining lift and drag coefficients is used instead of a table-look-up scheme because it is easier to input new aerodynamic data and it is easier to obtain partial derivatives from an analytic form.

3.2.4.3 Optimization Problem

The problem is to find the control variable histories $(T_p, T_a, \alpha, i, \delta_F)$ which minimize the annoyance function over the time interval $t \in (t_o, t_f)$ subject to the equations of motion with specified initial conditions and the control bounds

$$0 \leq T_p \leq (T_p)_{\max} \quad (3.2-18)$$

$$0 \leq T_a \leq (T_a)_{\max} \quad (3.2-19)$$

$$i_{\min} \leq i \leq i_{\max} \quad (3.2-20)$$

$$\alpha_{\min} \leq \alpha \leq \alpha_{\max} \quad (3.2-21)$$

Furthermore, any function of terminal values of the states or time t_f can be constrained. For some cases an inflight constraint was placed on the maximum allowable noise level at any listener as

$$PNL_i(Y_i, T) \leq 95 \text{ PNdB} \quad (3.2-22)$$

This constraint is a mixed function of the state and control variables.

At first, angle of attack was used as a control variable. However, a phugoid motion developed which was difficult to control. This is seen in Fig. 3.2-23A, where for constant α an unstable oscillation in γ developed. Thereafter, pitch angle, θ , was used as the control, where $\theta = \gamma + \alpha$. Figure 3.2-23B shows that for a constant pitch angle command, the oscillation is eliminated. Constant θ implies that as γ increases, α will decrease. By Eq. 3.2-13, $\dot{\gamma}$ is reduced so that the motion of γ is stabilized.

Steepest descent¹⁵ is a first-order gradient optimization algorithm that improves the performance index on each iteration. Linear theory is used to develop influence or adjoint functions about a nominal path. The impulse response function is then determined which relates changes in the control along the trajectory to the change in the cost. Stationarity is reached when no arbitrary change in the control variables will, to first order, improve the cost. This occurs when the impulse response function is near zero. Unfortunately, as the impulse response function becomes small, it becomes increasingly more difficult to reduce it. In fact, to drive the impulse response function to zero, it takes an infinite number of steps. Therefore, convergence slows when near the optimum path in the state space.

The steepest descent method can also satisfy terminal constraints on functions of the state variables. Again, the impulse response function for each constraint is formed. In a linear space (Hilbert space) approximated by small variations in the state and control variables from a nominal path, each control variable can be decomposed into an orthogonal set of components. Each component allows a constraint to be met while not affecting the other constraints or the performance index. The control component orthogonal to the impulse response functions of the constraints is used to improve the performance index by the steepest descent method. The impulse response functions and the adjoint variables (which relate changes in the state at any time along the trajectory to changes in the cost or the terminal constraints) are useful in themselves for conducting a sensitivity study on the trajectory.

Included in this steepest descent study are inflight inequality constraints on the control variables and/or state variables.^{15,16} Constraint functions which are only functions of the control (Eqs. 3.2-18 to -20) are included without any important programming changes. However, for constraint functions which explicitly contain the state variable and the control variable (i.e., Eqs. 3.2-21 and -22) additional programming is necessary because on the constraint boundary the control is a function of the state variable.* This dependence is explicitly accounted for by modification of the adjoint differential equations.

Each listener is represented by an augmented state equation

$$\dot{g}_i = 10 \text{ PNL}_i / K \quad (3.2-23)$$

so that Eq. 3.2-7 becomes

$$PI = \sum_{i=1}^n P_i S_i [K \log (g_i / T_o)]_{t=t_f} \quad (3.2-24)$$

It is not necessary to perform the backward integration of the adjoint equations associated with the augmented states; thus, the addition of more listeners is relatively simple and not costly in computer time. The performance index can also be updated without much difficulty as better noise models become available.

For rapid convergence, each control variable is weighted relative to one another, and this weighting matrix is included in the program as a function of time. The choice of the weighting matrix is found heuristically after a study of the initial convergence rate.

* Note that since pitch angle is the control variable, the angle of attack is a function of pitch angle and flight path angle. This mixed function of state and control variables adds the same complication as does the condition of Eq. 3.2-22.

The computer program is written in M.I.T.'s MAC language and is run on an IBM 360/75. The computer time required for a 100-sec trajectory operating at a 0.5-sec time step is approximately 45 sec/iteration. A typical run requires about 20-30 iterations for acceptable convergence.

3.2.4.4 Results

This analysis examines some general behavior patterns of minimum noise takeoff trajectories for STOL aircraft. In this context, minimum noise trajectories are obtained from various initial conditions to a final altitude of 5,000 feet.

The first attempt to minimize noise used a constant flap angle of 60 deg and a maximum total engine thrust of 22,910 lbs. The initial conditions on the state variables were $h = 400$ feet, $V = 100$ ft/sec, $\gamma = 15.4$ deg, and $R = 2,280$ feet. By modulating the pitch and angle of incidence as shown in Figs. 3.2-24D and E, and by maintaining the primary and augmentor thrust at their maximum values, Figs. 3.2-24A, B, and C show that the vehicle quickly settles into a state of maximum sustainable flight path angle ($\gamma = 25$ deg). As seen in Fig. 3.2-25, the unconstrained PNL exceeds 100 PNdB in the vicinity of listener 1. While noise sensitive tracks for conventional jet aircraft range from 4 to 8 miles, this figure shows that no significant noise (70 PNdB is about the daytime background noise level in a residential neighborhood) is detected beyond a range of 2 miles.

For comparison, another run was made with the same initial conditions, but with the maximum PNL constrained to 95 PNdB. The noise profile for this case (Fig. 3.2-26) shows that the cost of reducing the peak noise at listener 1 is a slight increase in overall annoyance (i.e., the performance index increases from 601 to 630 dB). The greatest increase in annoyance is suffered by listener 2. Note that the vehicle again settles to the same steady state as in the unconstrained case (Figs. 3.2-27A, B, and C). However, initially, the primary thrust (Fig. 3.2-27F) must be decreased from a maximum of 15,870 lbs to about 2,000 lbs in order to maintain the noise level at 95 PNdB. This indicates that it probably is not possible to constrain the PNL much below 95 PNdB. Note that in this case the velocity increases by decreasing the flight path angle. This is done to induce a rapid rise in altitude before reaching listener 2. However, the altitude remains fairly constant as the aircraft passes over listener 1.

Noting that the STOL vehicle would initially climb as fast as possible, initial conditions were chosen closer to the steady-state value of maximum rate of climb for this aircraft. In this case the angle of attack is constrained to its lower limit of -12 deg during the transient phase of the trajectory. As before, the vehicle settles to the same steady state of maximum sustainable flight path angle (Figs.

3.2-28A, B, and C). Although the peak noise detected by listener 1 is about the same as in the case tested earlier (Fig. 3.2-29), the overall annoyance has been reduced by starting at a higher rate of climb. Another set of initial conditions was tested ($V = 123$ ft/sec, $\gamma = 23.37$ deg, $h = 400$ feet, $R = 2,280$ feet). Again, the trajectory settled to the same steady-state condition of maximum flight path angle.

Both the unconstrained and constrained noise cases were repeated, this time modulating the flap angle as well as the four control variables used earlier. With the addition of the flap as a control variable, C_L and C_D became functions of F as well as of C_J and δ . Again, maximum flight path angle is achieved in steady state (Figs. 3.2-30A, B, C and -31A, B, C). By starting the transient phase with a flap angle near 20 deg and by decreasing the flap to 12 deg and maintaining this value during steady state, the vehicle climbs at a higher velocity and reaches terminal altitude about 30 sec faster than the constant 60-deg flap case. In both the constrained noise and unconstrained noise cases, the angle of attack is constrained to its upper limit of 15 deg during the transient phase.

Minimum noise trajectories for ground takeoff to 5,000-foot terminal altitude were also generated for both the constrained noise and unconstrained noise cases. Again, maximum flight path angle is achieved in steady state. Note that since the maximum total thrust is less than that used in the above cases (18,600 lbs), the maximum flight path angle has been reduced from 23 deg to 20 deg (Figs. 3.2-32B and -33B).

As the ground takeoff trajectory began to converge, there developed the unrealistic situation of negative altitude during the transient phase. To avoid this and to avoid modeling the airplane dynamics on the runway, the initial velocity was increased or decreased by some fixed amount dependent on the initial $\dot{\gamma}$ from the last iteration. In each case, the initial downrange was adjusted by a linear extrapolation. This explains the slight difference in initial velocity seen in Figs. 3.2-32C and -33C.

The angle of incidence is constrained to its lower limit of 18.5 deg for the entire trajectory in each ground takeoff case. Earlier results, where the angle of incidence could vary between -60 deg to +60 deg, indicated that the angle of incidence tended to remain around zero.

In the constrained ground takeoff case, noise is constrained to 95 PNdB at both microphone one (0.5 n.mi. downrange) and microphone two (1 n.mi. downrange). To compare the effect of microphone position the unconstrained ground takeoff case was repeated with all microphones shifted 0.5 n.mi. downrange. Steady-state conditions were the same in both cases, but the time to reach steady state was less when the first microphone was downrange 1.0 n.mi. instead of 0.5 n.mi.

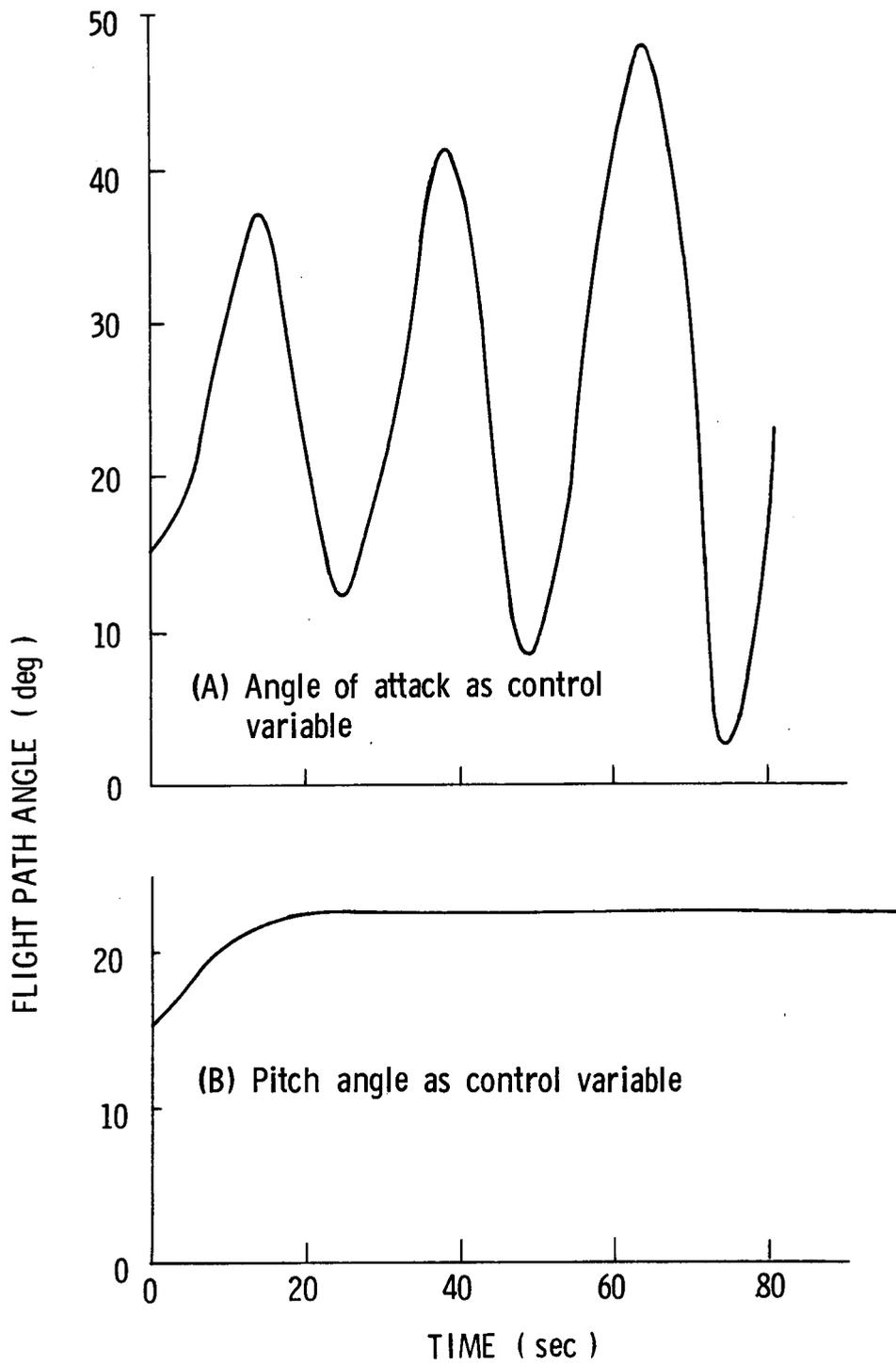


Figure 3.2-23 Elimination of Phugoid Oscillation by Using Pitch Angle Rather Than Angle of Attack as the Control Variable

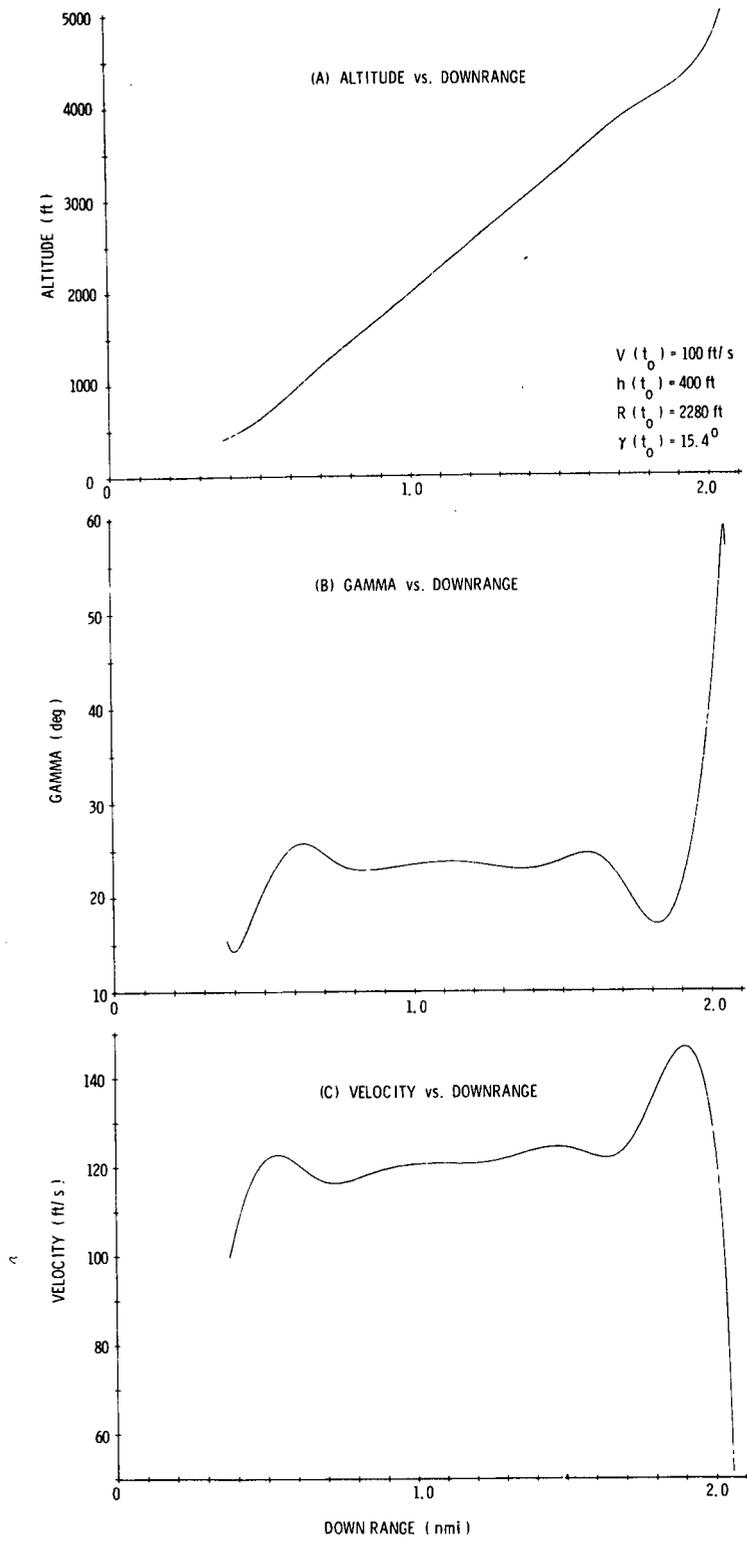
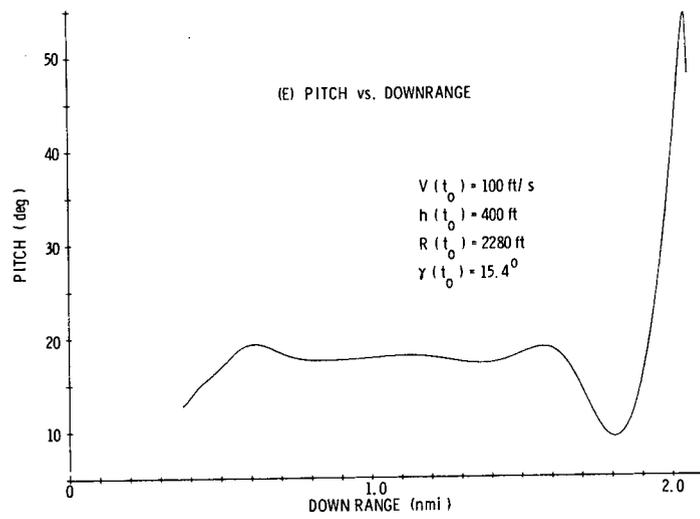
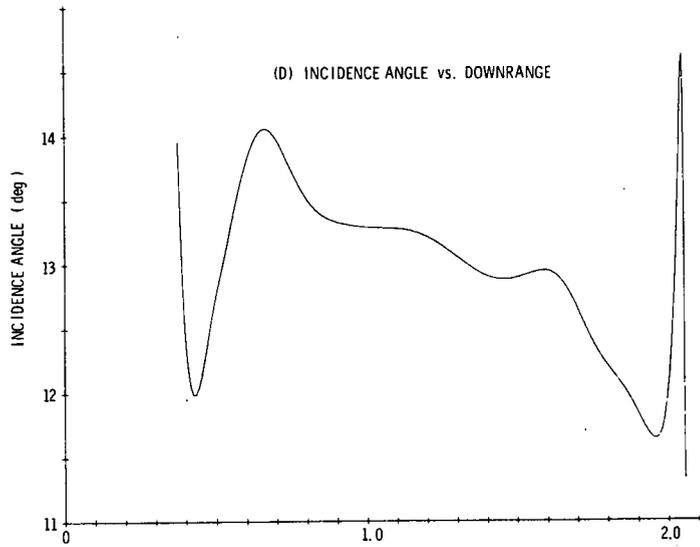


Figure 3.2-24 State and Control Variable Histories with Maximum PNL Unconstrained (Flap Angle Fixed at 60 Deg)



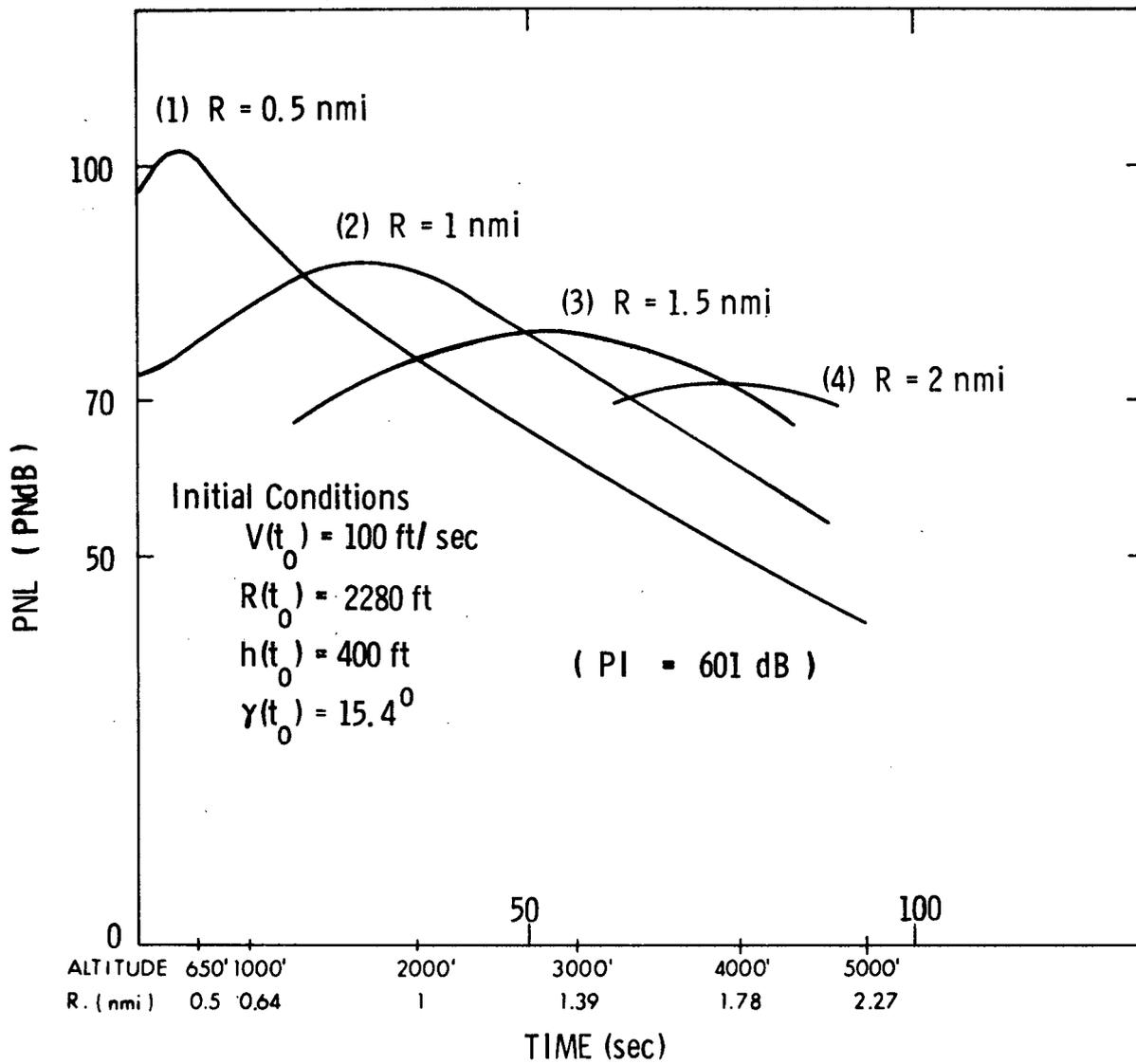


Figure 3.2-25 Noise Profiles for the First Four Listeners with Maximum PNL Unconstrained (Flap Angle Fixed at 60 Deg)

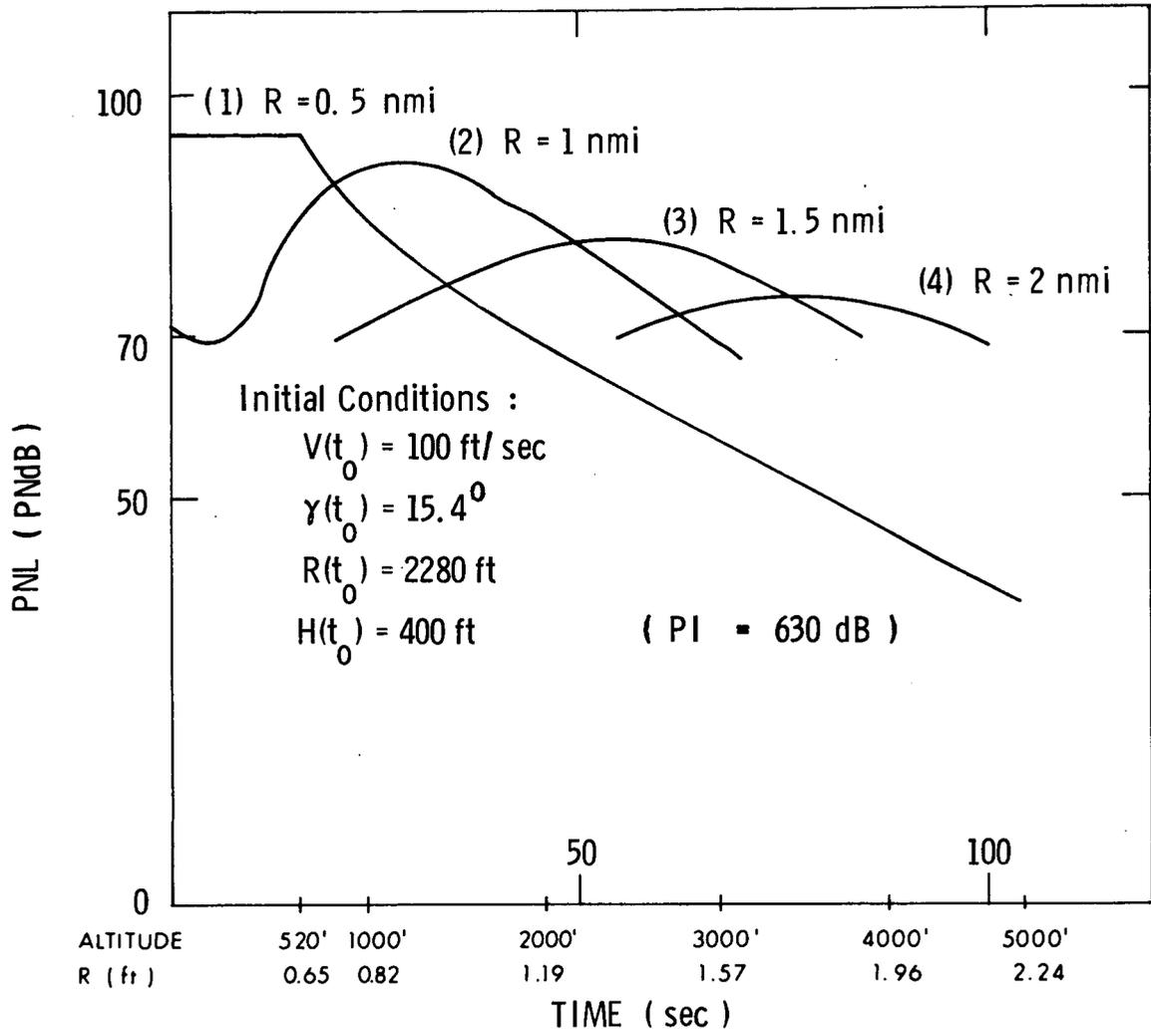


Figure 3.2-26 Noise Profiles for the First Four Listeners with Maximum PNL Constrained to 95 PNdB (Flap Angle Fixed at 60 Deg)

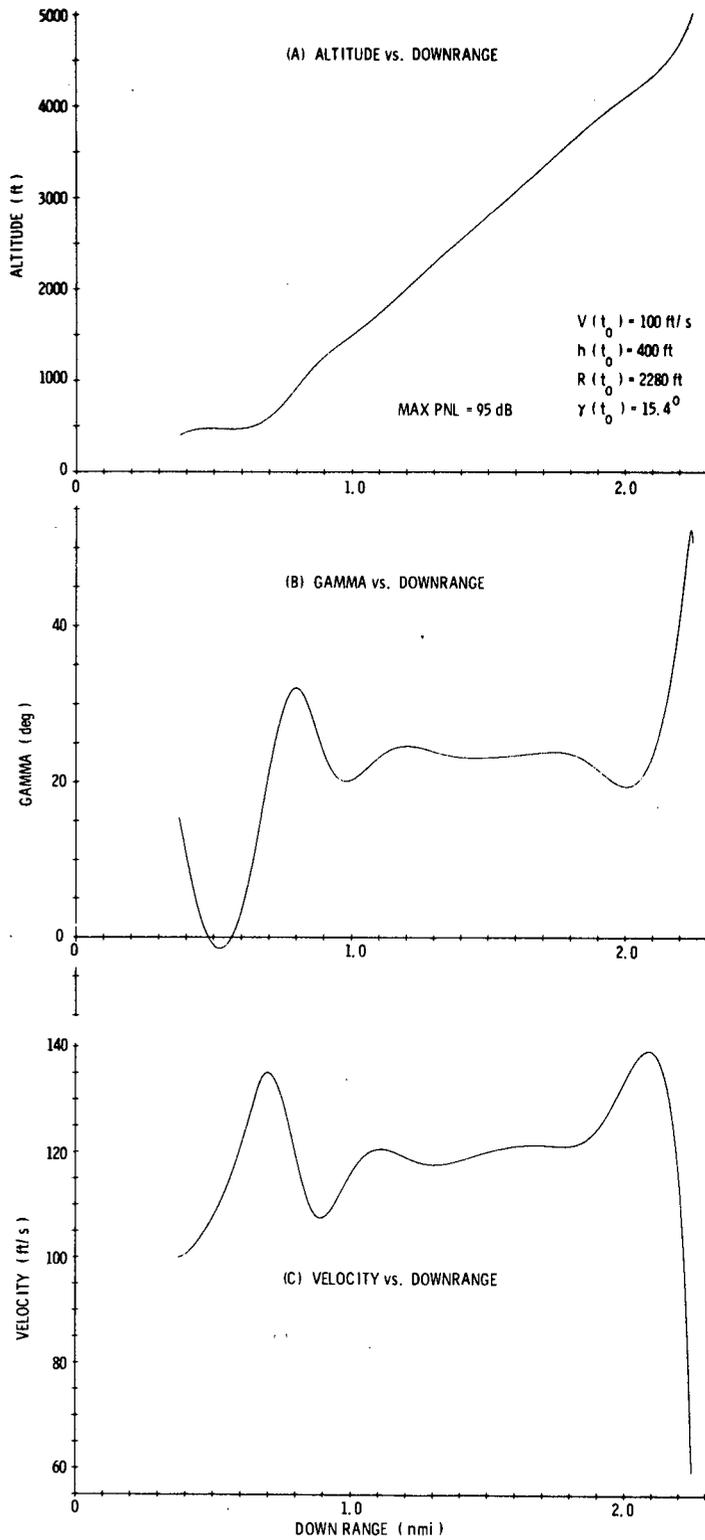
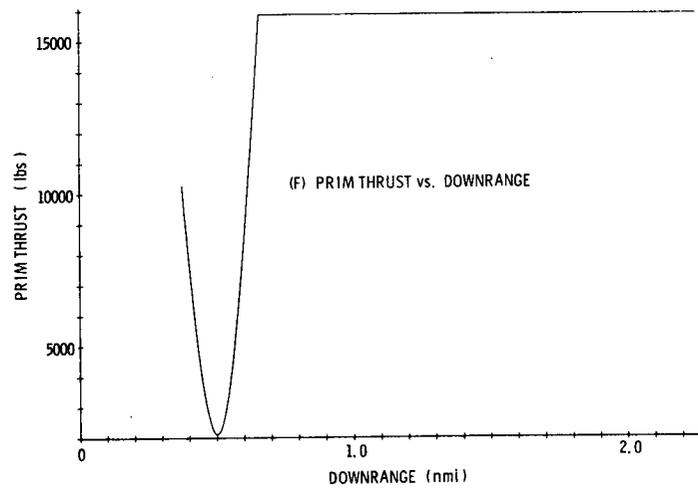
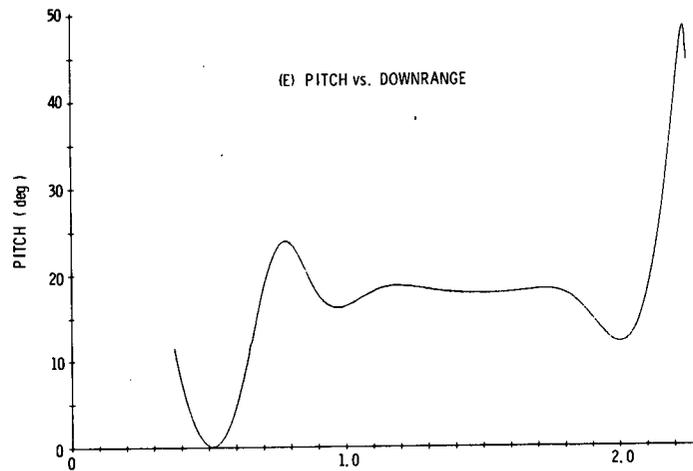
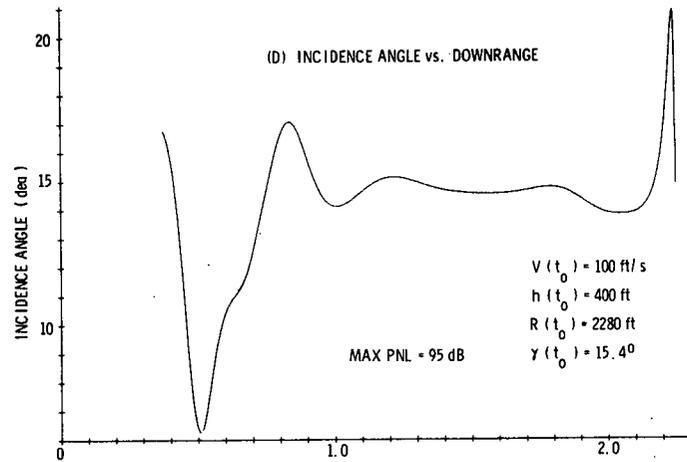


Figure 3.2-27 State and Control Variable Histories with Maximum PNL Constrained to 95 PNdB (Flap Angle Fixed at 60 Deg)



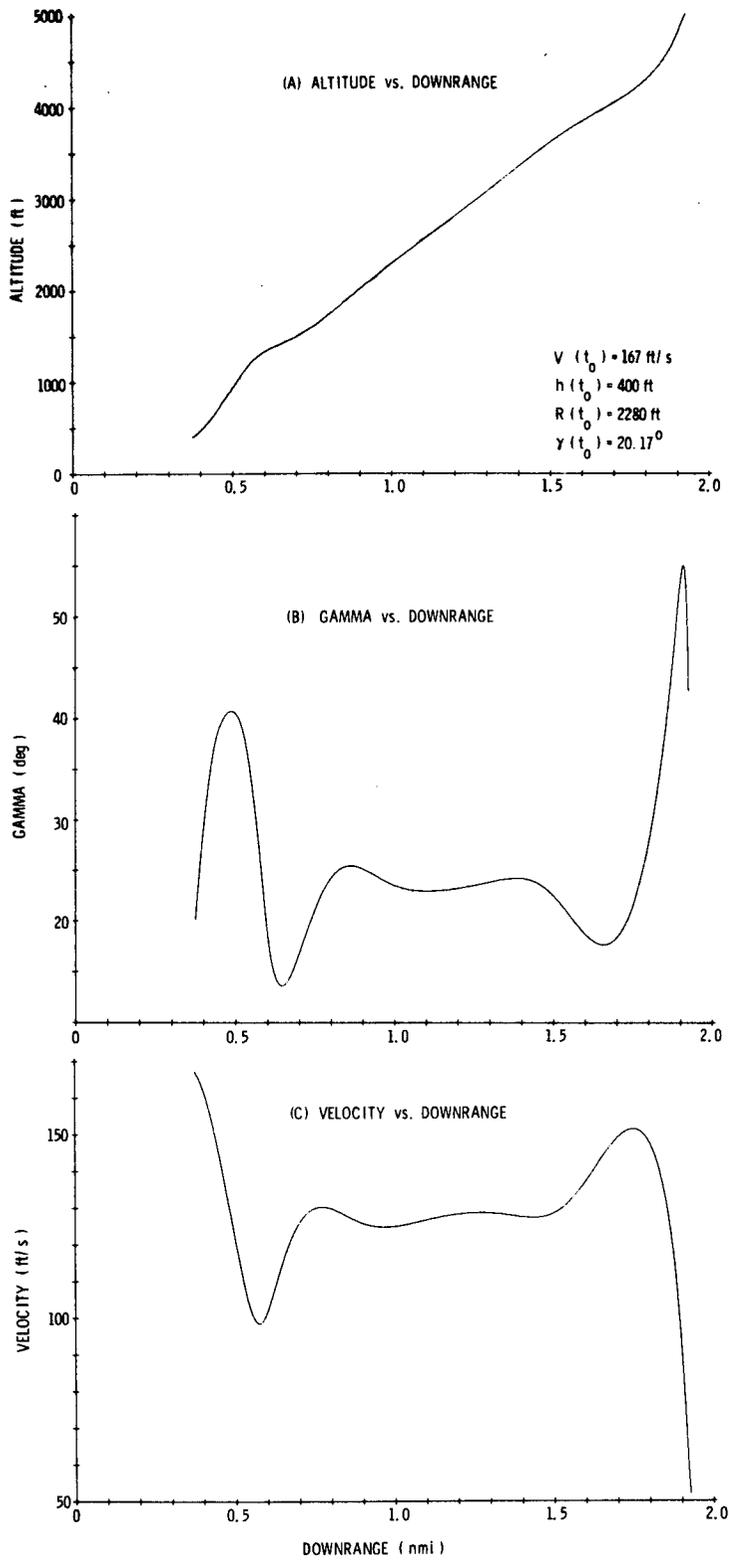
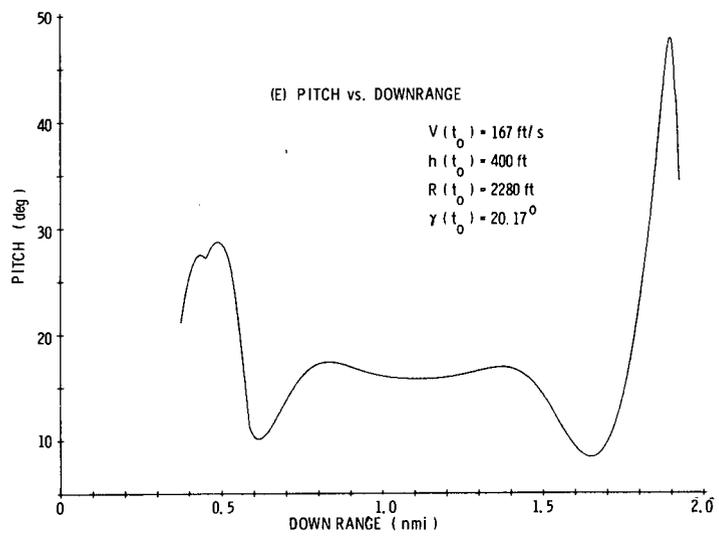
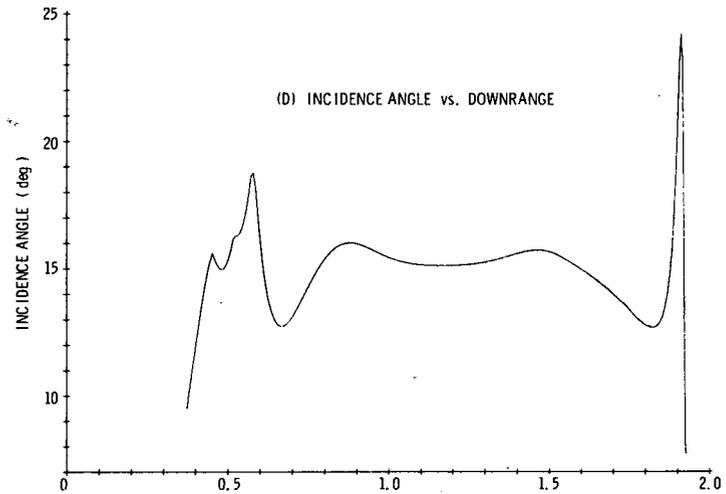


Figure 3.2-28 State and Control Variable Histories with Maximum PNL Unconstrained (Flap Angle Fixed at 60 Deg; Different Initial Conditions)



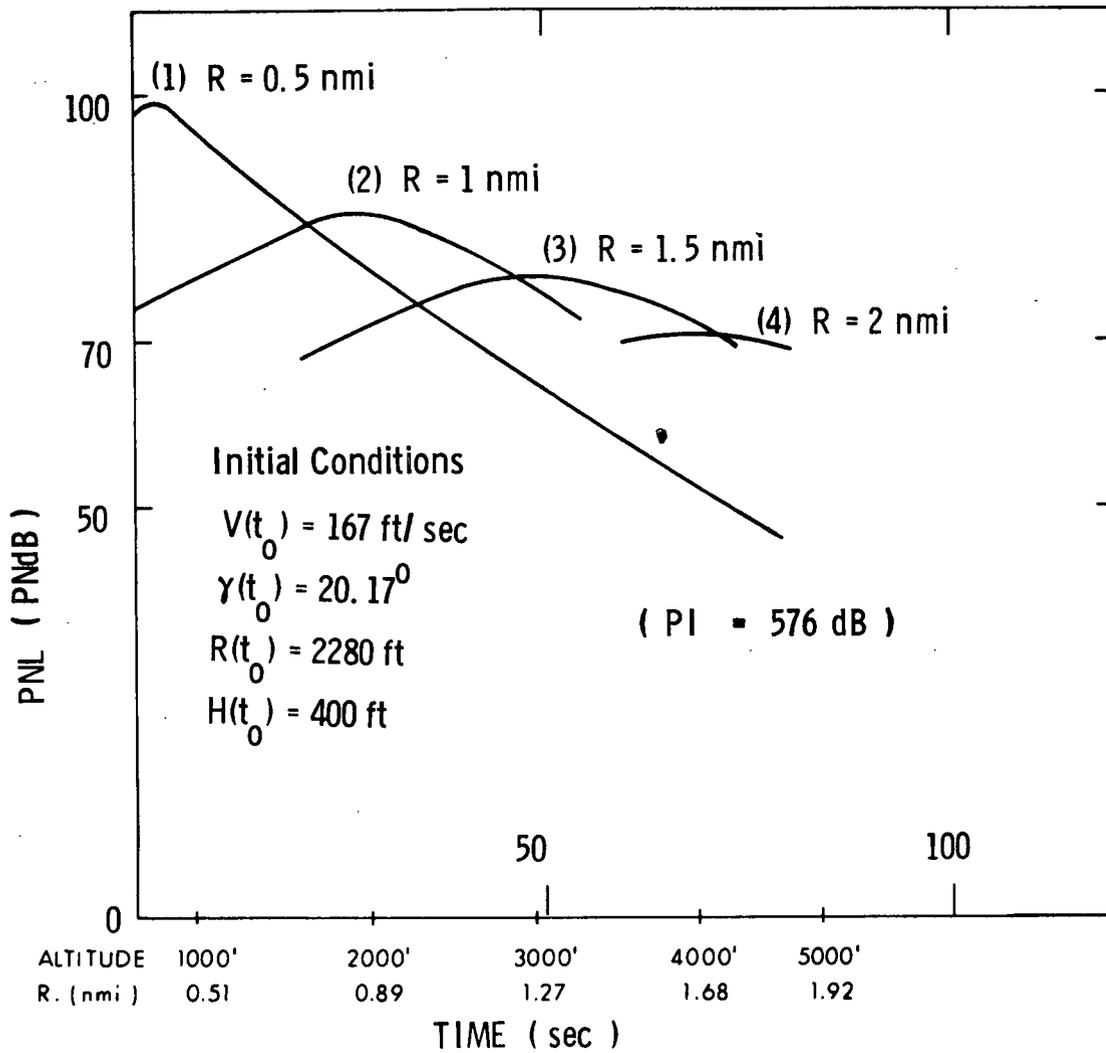


Figure 3.2-29 Noise Profiles for the First Four Listeners with Maximum PNL Unconstrained (Flap Angle Fixed at 60 Deg; Different Initial Conditions)

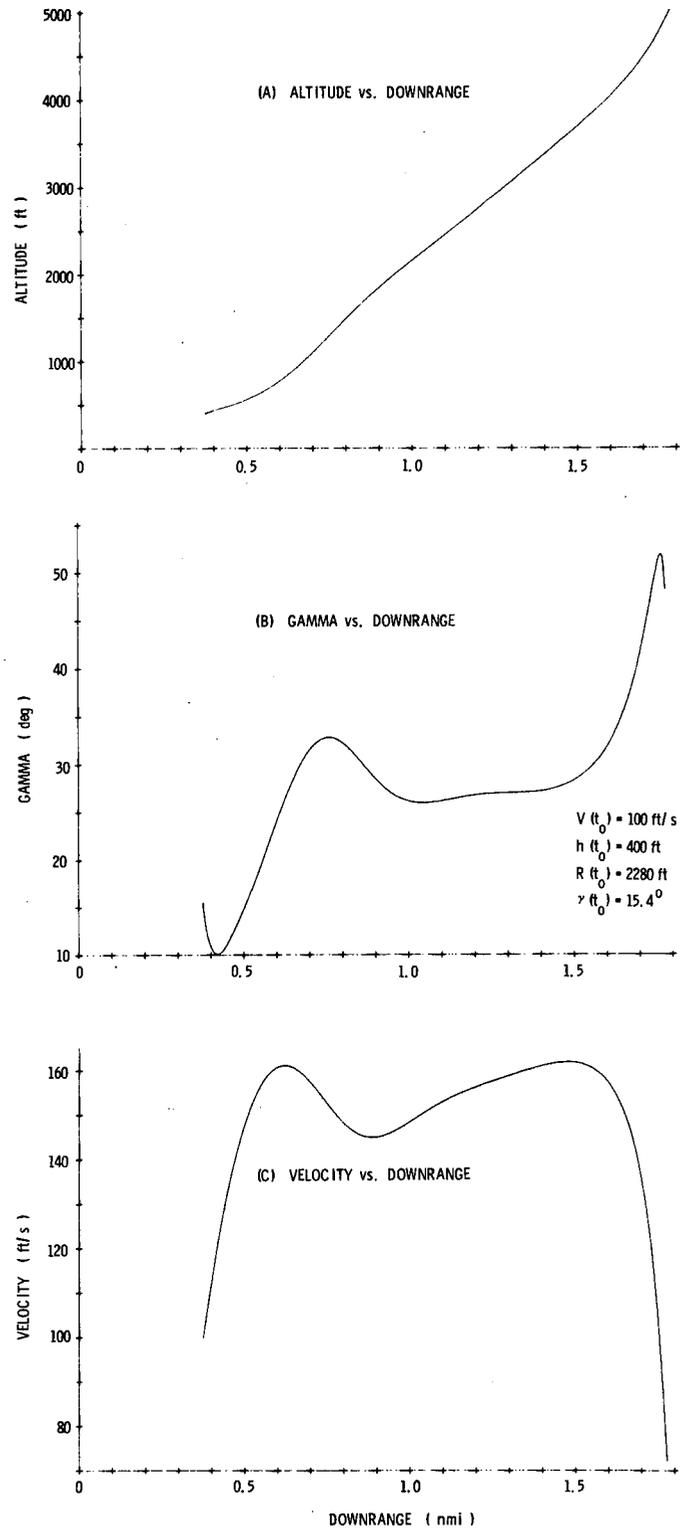


Figure 3.2-30 State and Control Variable Histories with Maximum PNL Unconstrained (Flap Controllable; Original Initial Conditions)

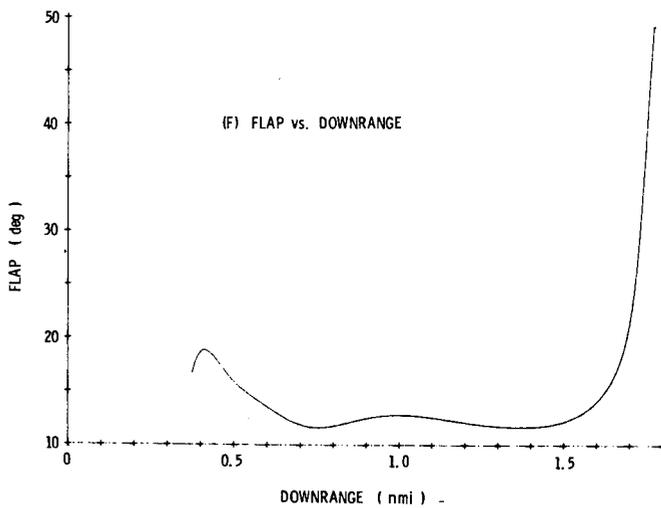
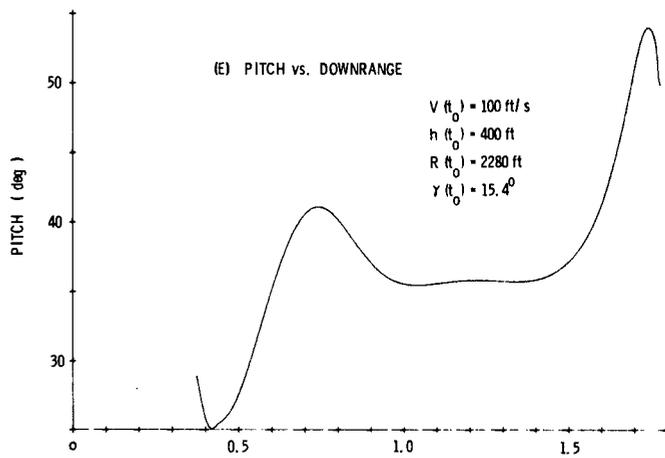
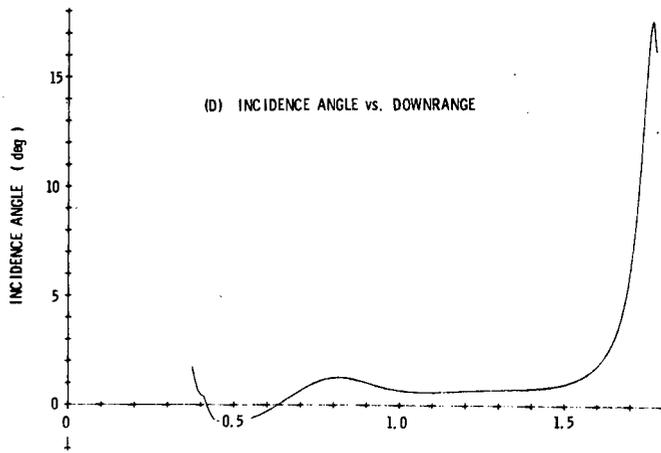


Figure 3.2-30
(cont.)

a

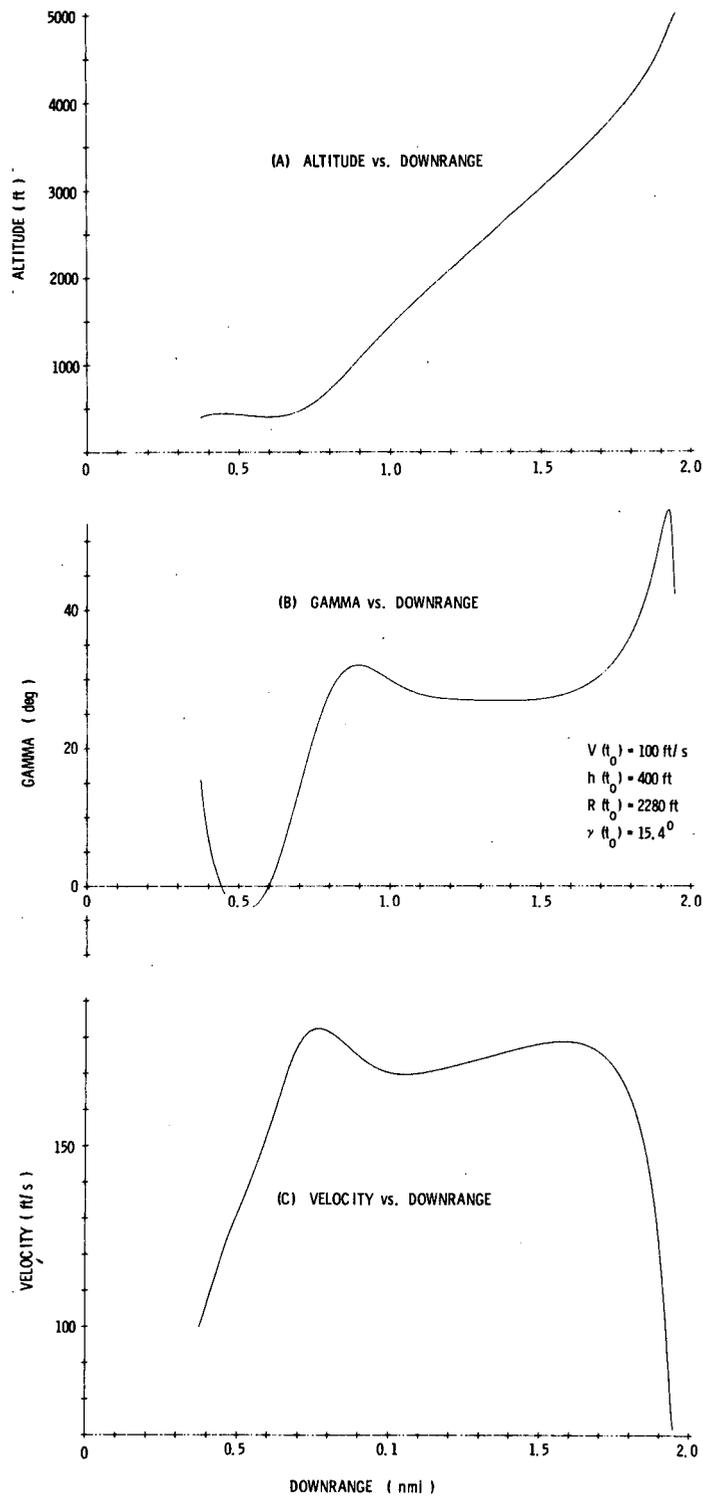


Figure 3.2-31 State and Control Variable Histories with Maximum PNL Constrained to 95 PNdB (Flap Controllable; Original Initial Conditions).

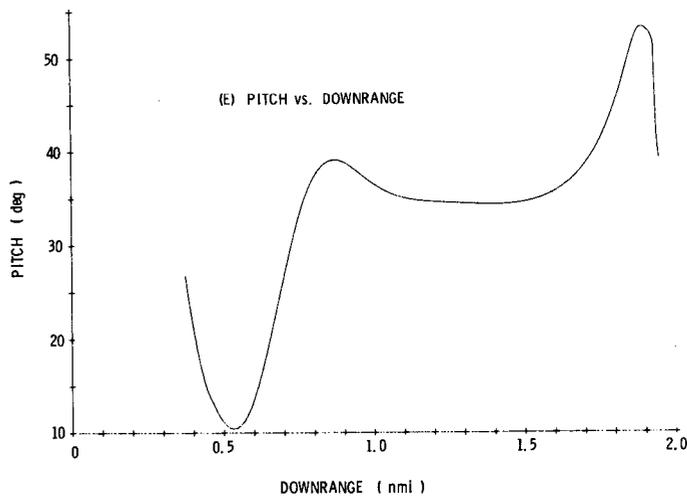
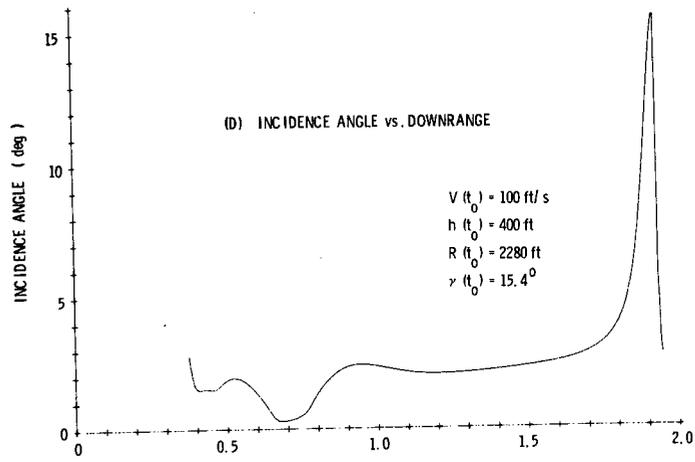


Figure 3.2-31
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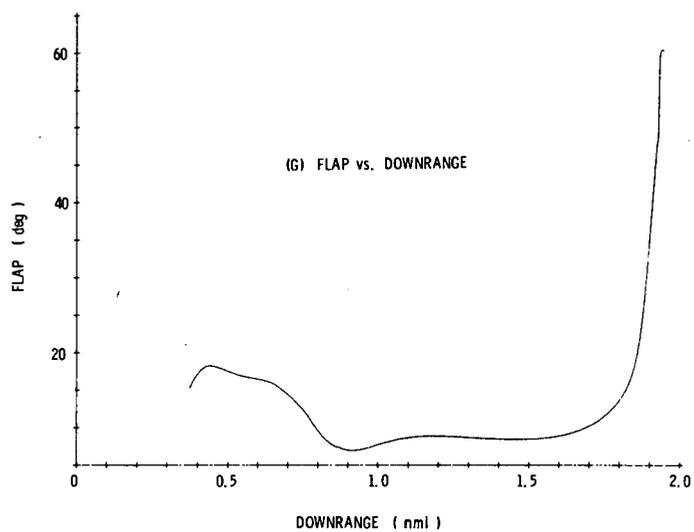
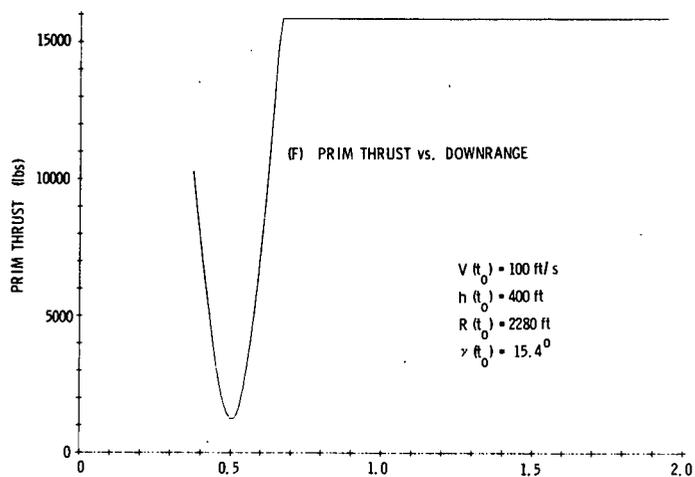


Figure 3.2-31
(cont.)

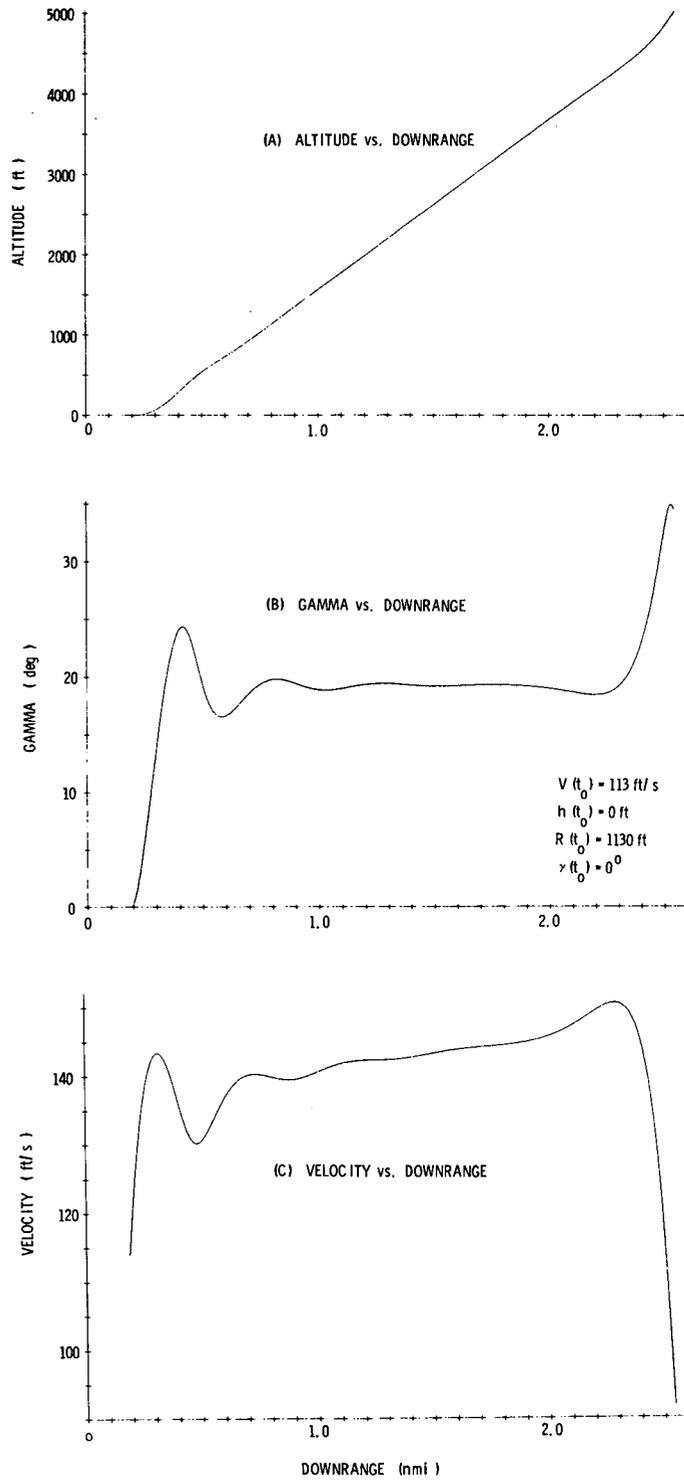
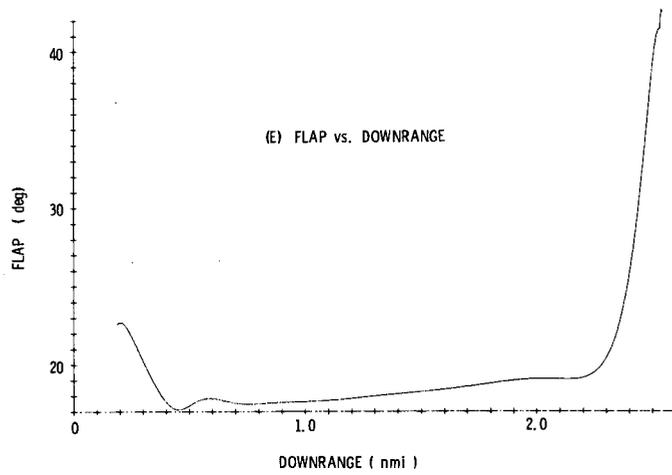
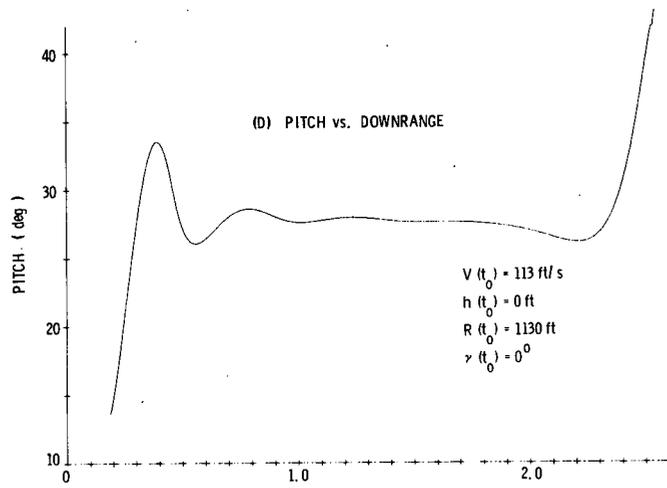


Figure 3.2-32 State and Control Variable Histories with Maximum PNL Unconstrained (Flap Controllable; Ground Takeoff)



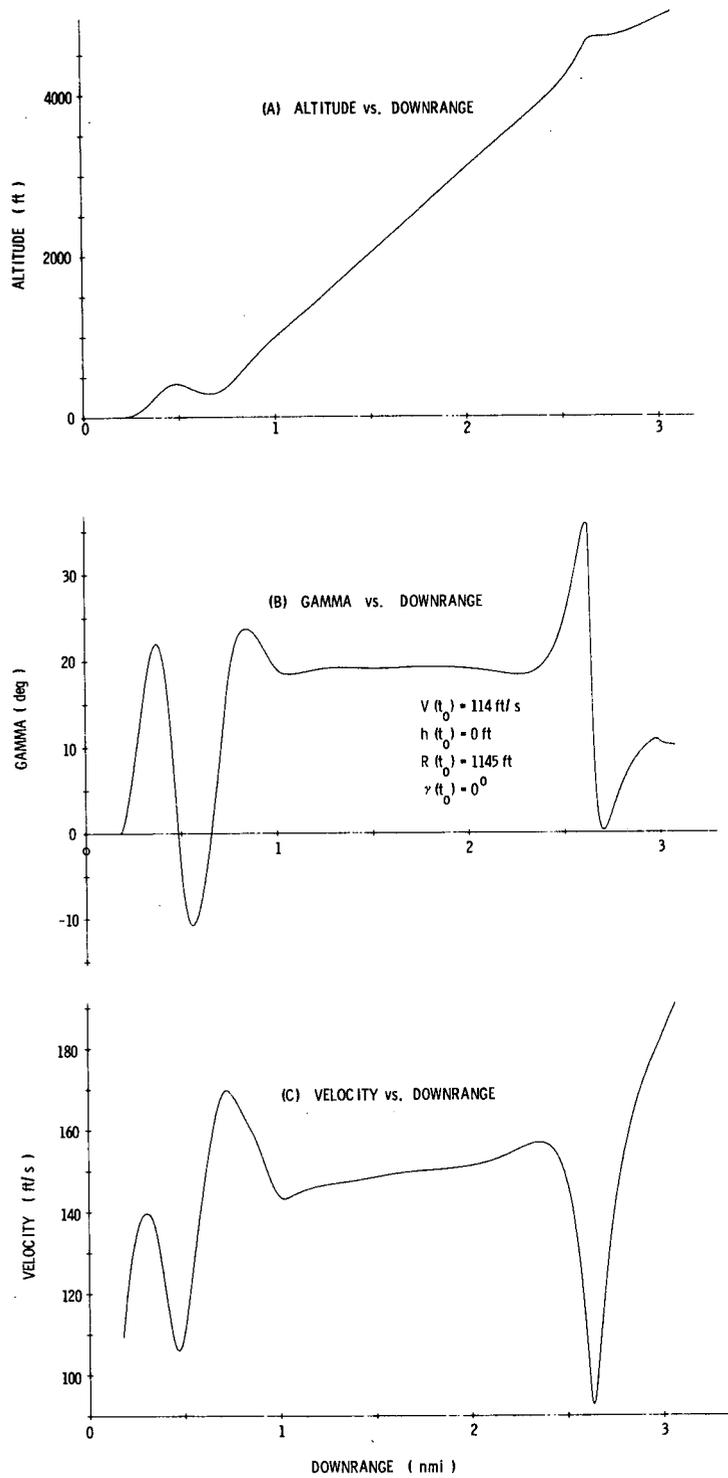
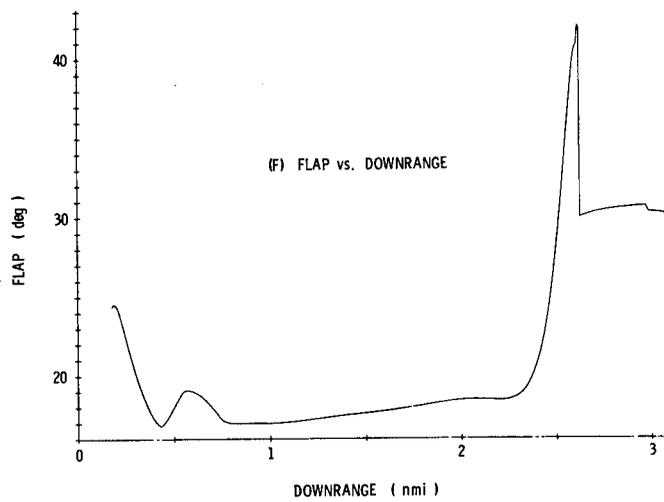
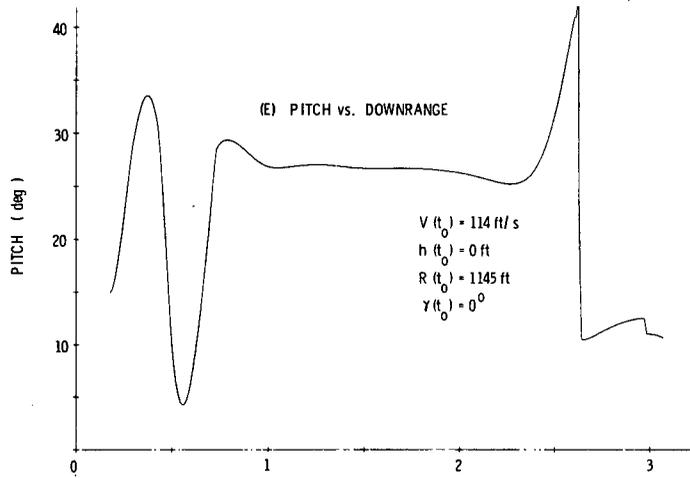
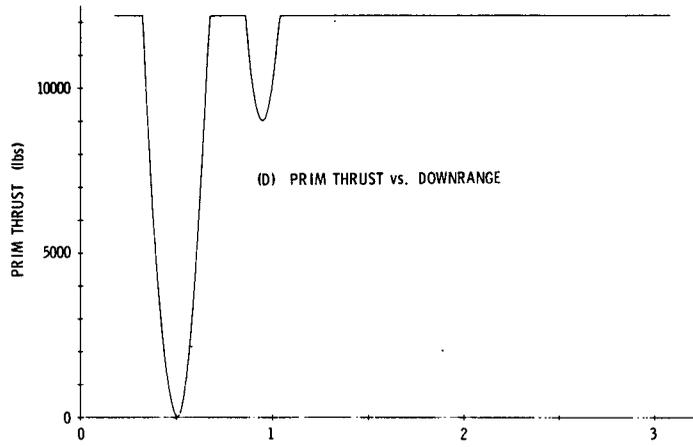


Figure 3.2-33 State and Control Variable Histories with Maximum PNL Constrained to 95 PNdB (Flap Controllable; Ground Takeoff)



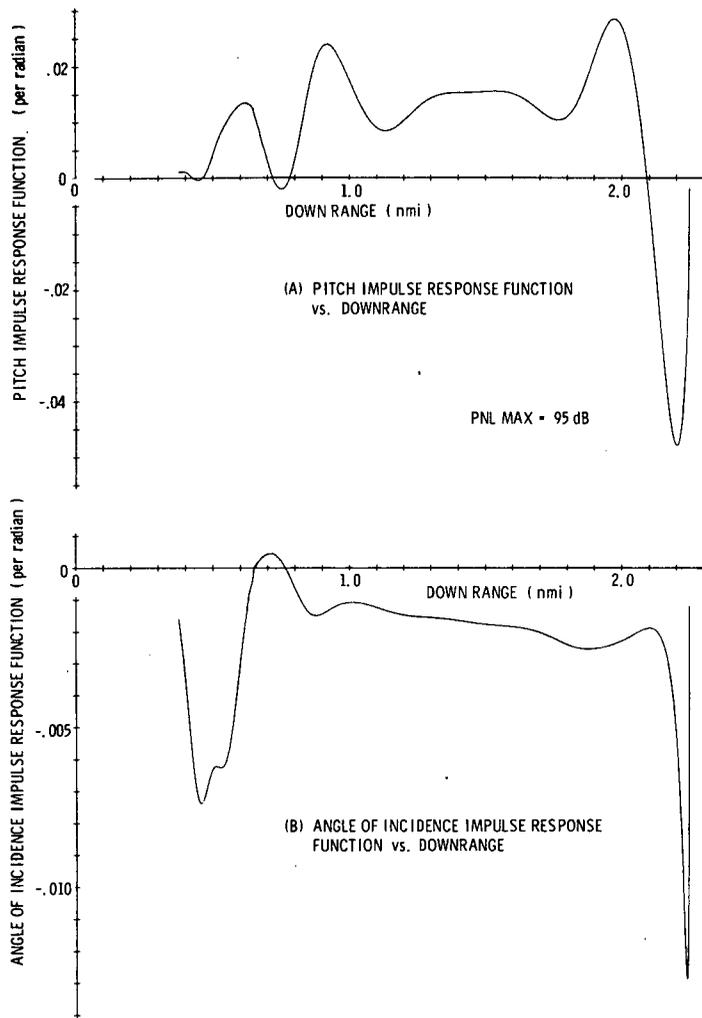


Figure 3.2-34 Impulse Response Function for Two Control Variables with Maximum PNL Constrained to 95 PNdB (Flap Angle Fixed at 60 Deg; Original Initial Conditions)

For the constrained case the maneuvers are quite severe and unrealistic. In fact, if a microphone were placed 0.75 n.mi. from the runway (in addition to the 0.5-n.mi. and 1.0-n.mi. locations), the instantaneous noise level constraint of 95 PNdB would be violated. This gives a case for concentrating more microphones at the beginning of the ground track so that if the noise level constraint can be satisfied it will be satisfied more uniformly along the ground track, and hopefully a smoother trajectory will be generated.

At the end of each trajectory, a flare maneuver occurs where the velocity goes to zero and the altitude rises sharply. This occurs because the terminal condition was chosen to be an altitude of 5,000 feet to save computer time. The program uses this flare to obtain a slight decrease in the performance index. However, if the terminal altitude were to be increased, the length of the steady-state climb would also increase. Therefore, the flare maneuver can be ignored, and the trajectory assumed to end at the 5,000-foot altitude in the steady state.

In using steepest descent, the question often arises as to how close results really are to optimum. As seen in Figs. 3.2-34A and B, the impulse response functions for pitch and angle of incidence are quite small. This means that to a first-order approximation a 1-deg change in either of these control variables over a 100 sec trajectory would change the performance index by less than 0.001 PNdB. Since an instantaneous change of 3 PNdB is required for the human ear to detect any change at all, this improvement would be insignificant.

3.2.4.5 Conclusions and Recommendations

A steepest descent optimization program was used to determine minimum-annoyance flight paths on takeoff and climbout for a jet powered STOL vehicle. The problem was 2-dimensional in that listeners were strung out at 0.5-n.mi. intervals along the extended runway centerline.

The flight paths obtained indicate that if no listeners have constraints on their Perceived Noise Level, then the vehicle should use its maximum climb angle and maximum thrust to maximize the distance to the listeners. If the listeners have constraints on their maximum PNL however, a large thrust reduction can be employed to reduce noise near the closest listener, followed by an increase to maximum thrust and maximum flight path angle.

These results hold true (1) for several cases of initial conditions, including ground takeoff, (2) for the augmentor flap either fixed or controllable, and (3) for two values of thrust-to-weight ratio.

The results prove interesting and useful, in that an operator knows that he should employ a maximum climb angle takeoff to provide minimum total annoyance to listeners distributed along his flight path. For particularly sensitive areas close in to the runway however the thrust cutbacks used to reduce noise were extreme, being both uncomfortable and unsafe. What is needed are some additional runs with less extreme thrust reductions for a comparison in total annoyance.

As for additional work, it would be useful to expand the group of listeners to three dimensions, such that curved flight paths could be examined. Moderate reductions in PNL (3-5 PNdB or more) at a given point should be possible by the proper choice of 3-D flight paths. In conjunction with this, the plots should include the PNL contours for a given run, as this provides more information than just the PNL at a particular group of listeners. Finally it would be worthwhile from an operator's viewpoint to find out just what these noise-optimum flight paths cost in additional fuel or time. It may be that there is no significant difference between standard and noise optimum flight paths.

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3.3 WIND CONDITIONS AFFECTING LANDING

This section describes wind conditions as they affect the final approach and landing of an aircraft. There are three types of wind conditions which are treated here: first, mean wind, which is the velocity of the air relative to the ground at some reference altitude; second, boundary layer shear, which is the vertical variation of the horizontal wind velocity; and third, turbulence, which is a random variation of wind velocities from the steady-state (mean wind and boundary layer shear) velocities.

The prediction of mean wind for a given airfield is discussed in Section 3.3.1. Statistical methods are considered for prediction of percentage occurrence of adverse wind conditions, as well as improved prediction of wind velocity provided to the pilot for each landing.

Boundary layer shear predictions are considered in Section 3.3.2. The shear is primarily dependent on mean wind and on turbulence. Unfortunately, the dependence on turbulence is not easily formulated and the turbulence itself is not easily predicted. Therefore, some attempts have been made to relate the shear to more easily predictable quantities.

Sections 3.3.3 through 3.3.7 are concerned with turbulence. Turbulence is a random process, and hence predictions of turbulence velocities can only be made in a statistical sense. Basic properties of turbulence statistics are discussed in Section 3.3.3. Certain assumptions and simplifications are considered for validity, and are shown to support a Gaussian model. Section 3.3.4 discusses the mechanics of turbulence without ground effect, and presents some classic descriptions of turbulence as given by von Karman and Dryden. In Section 3.3.5, the effect of the ground is considered. The proximity of the ground makes the vertical statistics distinct from the horizontal statistics. Also, due to the mean wind and boundary layer shear, the downwind statistics become distinct from the crosswind statistics. With these considerations, the model of the turbulence is further refined, and some numerical results are presented.

The turbulence has now been described as a function of space and time, and must be converted into the single coordinate of elapsed time of the aircraft along its flight path. The way in which this is done is described in Section 3.3.6.

Special causes of turbulence, which do not fit into the framework used throughout Sections 3.3.3 through 3.3.6, are described in Section 3.3.7. Section 3.3.8 presents conclusions concerning a turbulence model suitable for analysis of an aircraft's ability to withstand normal service, with suggestions for further studies to improve that model.

3.3.1 Steady Winds

Currently, landing fields provide the pilot with measurements of the speed and direction of surface winds close to the runway complex, which the pilot utilizes as predictions of wind conditions for his subsequent landing. Although the current method is quite satisfactory, the accuracy of these wind predictions could be improved by filtering out the turbulence measurement, thereby measuring only the steady wind velocity. Figure 3.3-1 shows the power spectral density of wind velocity measured at a ground location. The distinction between the steady and turbulent wind velocities is dependent upon frequency: the border between the two is the local minimum of the spectral density, which occurs at a frequency of 1 to 10 cycles per hour depending on thermal conditions. The turbulence includes high frequencies which tend to distort wind predictions. With knowledge of this power spectral density, a technique such as Wiener filtering could greatly improve the prediction of wind speed and direction.

An aircraft operator is not only interested in the best estimate of wind conditions when he reaches his destination, but also in the probability of completing each scheduled flight. Information is available at many airfields concerning winds experienced over the past few decades, and these records provide a firm base for statistical analyses of future wind conditions. These records are published in various forms by U.S. government agencies¹ and generally provide such information as percentage occurrences of wind speeds and directions, visibilities and ceilings, and useful correlations of these occurrences.

Table 3.3-1 presents a 15-year set of typical ceiling/visibility data for Boston, Mass., from the USAF Air Weather Service.^{1a} From this information one can see that at Boston, VFR weather conditions (ceiling 1,000 feet, visibility 1 mile) occur about 89.6% of the time, CAT I conditions (200 feet, 1/2 mile) about 99.0% and CAT II (100 feet, 1/4 mile) about 99.6%.

Another report, from Lambert Field, St. Louis,^{1c} yields information such as the following: for the summer season, between noon and 5:00 PM local time, there were no reported occurrences (over a ten year period) of ceilings less than 300 feet; there were no reported occurrences of winds over 15 knots for ceilings under 800 feet; and for ceilings up to 3,000 feet, winds of over 15 knots always came from the E or ESE and the visibility was greater than 1.5 miles. These latter conditions occurred only about 6% of the time. When all conditions of ceiling are included, winds exceeded 15 knots about 0.3% of the time, and generally came from between E and S. For summertime afternoon landings at this field, therefore, the operator can depend on visibility of more than 1/2 mile and ceiling over 300 feet (no conflicting reports over a ten year period). He will have a 99.9% chance of

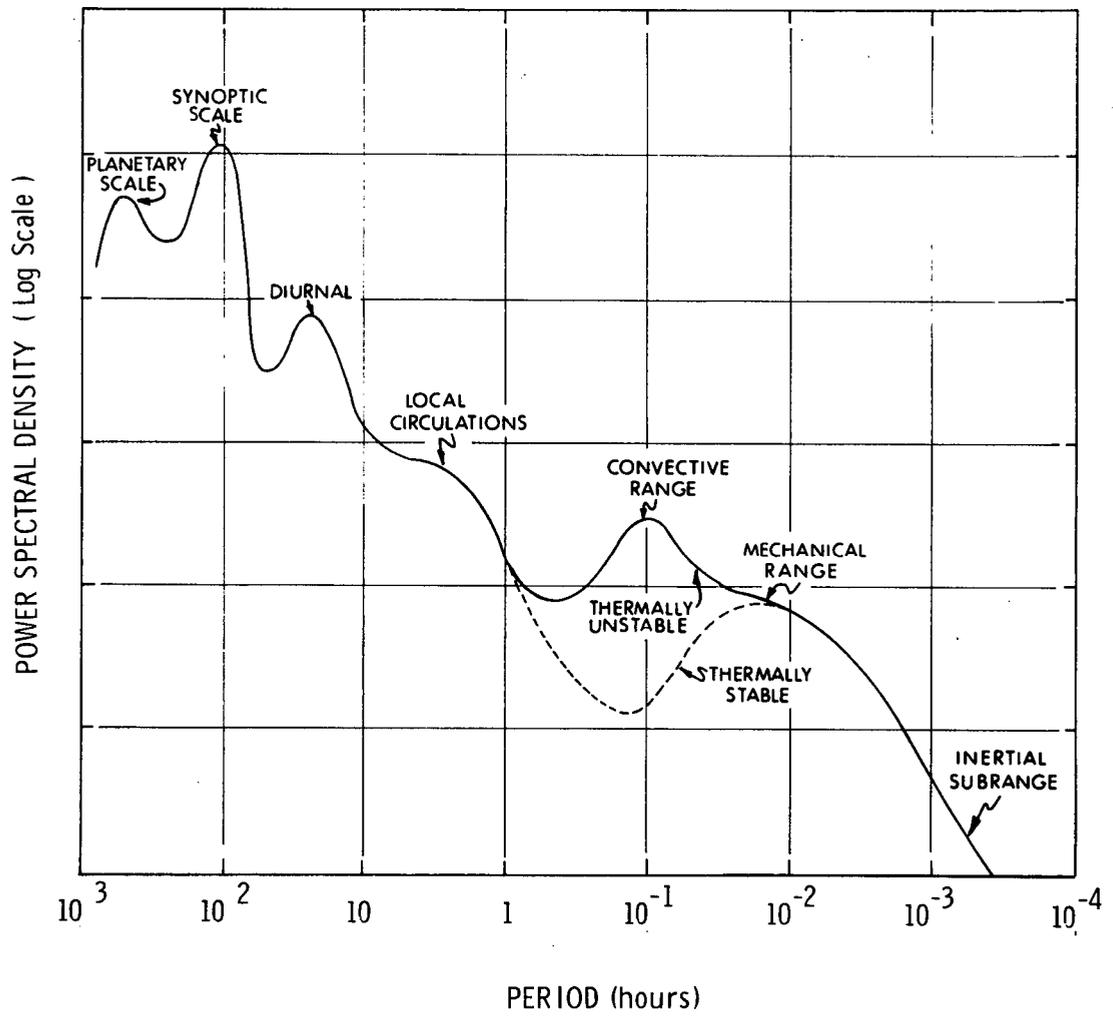


Figure 3.3-1 Power Spectral Density of Surface Winds Measured at a Ground Location (Ref. 14)

CEILING (FEET)	VISIBILITY (STATUTE MILES)												
	≥ 10	≥ 6	≥ 5	≥ 4	≥ 3	≥ 2½	≥ 2	≥ 1½	≥ 1	≥ ¾	≥ 5/16	≥ ¼	≥ 0
NO CEILING	15.9	18.5	19.2	19.8	20.1	20.3	20.5	20.5	20.5	20.6	20.6	20.6	20.6
≥ 20000	42.9	50.6	52.6	54.2	55.1	55.6	55.8	55.9	56.0	56.0	56.0	56.0	56.0
≥ 18000	43.5	51.3	53.3	55.0	55.9	56.4	56.6	56.7	56.8	56.8	56.8	56.8	56.8
≥ 16000	44.1	52.1	54.1	55.8	56.8	57.5	57.5	57.6	57.7	57.7	57.7	57.7	57.7
≥ 14000	45.7	54.0	56.2	58.0	59.0	59.4	59.7	59.8	59.9	59.9	59.9	59.9	59.9
≥ 12000	47.8	56.7	59.0	60.9	62.0	62.5	62.8	62.9	63.0	63.0	63.0	63.0	63.0
≥ 10000	49.5	58.9	61.3	63.4	64.5	65.0	65.4	65.5	65.6	65.6	65.6	65.6	65.6
≥ 9000	50.4	60.1	62.5	64.6	65.8	66.3	66.7	66.8	66.8	66.9	66.9	66.9	66.9
≥ 8000	51.6	61.6	64.2	66.4	67.6	68.2	68.5	68.6	68.7	68.7	68.7	68.7	68.8
≥ 7000	52.8	63.1	65.8	68.0	69.3	69.9	70.2	70.4	70.4	70.5	70.5	70.5	70.5
≥ 6000	54.2	64.9	67.7	70.0	71.3	71.9	72.3	72.4	72.5	72.5	72.5	72.5	72.5
≥ 5000	55.8	66.9	69.8	72.2	73.5	74.2	74.6	74.7	74.8	74.8	74.8	74.9	74.9
≥ 4500	56.7	68.0	70.9	73.3	74.7	75.4	75.7	75.9	76.0	76.0	76.0	76.1	76.1
≥ 4000	57.6	69.2	72.2	74.7	76.1	76.8	77.2	77.3	77.4	77.4	77.5	77.5	77.5
≥ 3500	58.5	70.3	73.4	76.0	77.4	78.1	78.5	78.7	78.8	78.8	78.8	78.8	78.8
≥ 3000	59.5	71.6	74.8	77.4	78.9	79.6	80.1	80.3	80.4	80.4	80.4	80.4	80.4
≥ 2500	60.5	73.0	76.2	78.9	80.5	81.2	81.7	81.9	82.0	82.0	82.1	82.1	82.1
≥ 2000	61.4	74.3	77.6	80.5	82.1	82.9	83.4	83.6	83.7	83.8	83.8	83.8	83.8
≥ 1800	61.8	74.8	78.2	81.1	82.7	83.5	84.0	84.3	84.4	84.4	84.5	84.5	84.5
≥ 1500	62.4	75.8	79.3	82.3	84.0	84.9	85.4	85.7	85.9	85.9	86.0	86.0	86.0
≥ 1200	63.1	77.1	80.8	83.9	85.8	86.7	87.4	87.7	87.9	88.0	88.0	88.0	88.1
≥ 1000	63.5	78.0	81.9	85.2	87.2	88.2	89.0	89.3	89.4	89.7	89.7	89.8	89.8
≥ 900	63.8	78.5	82.5	86.0	88.2	89.2	90.0	90.4	90.5	90.7	90.8	90.9	90.9
≥ 800	64.0	79.0	83.2	86.8	89.1	90.3	91.1	91.6	91.7	91.9	92.1	92.2	92.2
≥ 700	64.1	79.5	83.8	87.6	90.0	91.2	92.2	92.7	92.8	93.1	93.3	93.4	93.4
≥ 600	64.2	79.8	84.3	88.2	90.9	92.2	93.3	93.9	94.0	94.4	94.6	94.7	94.8
≥ 500	64.2	80.0	84.6	88.7	91.6	93.1	94.3	95.1	95.1	95.6	95.8	96.0	96.1
≥ 400	64.2	80.1	84.7	89.0	92.0	93.7	95.1	96.0	96.1	96.7	97.0	97.2	97.3
≥ 300	64.3	80.1	84.8	89.1	92.2	94.0	95.5	96.7	96.8	97.5	98.0	98.4	98.6
≥ 200	64.3	80.1	84.8	89.1	92.3	94.0	95.6	96.9	97.0	97.8	98.4	99.0	99.6
≥ 100	64.3	80.1	84.8	89.1	92.3	94.0	95.6	96.9	97.0	97.8	98.4	99.1	99.9
≥ 0	64.3	80.1	84.8	89.1	92.3	94.0	95.6	96.9	97.0	97.8	98.4	99.2	100.0

Table 3.3-1 Percentage Occurrence of Ceiling/Visibility Conditions for Boston, Mass.
(Hourly Observations from 1949-1965, All Hours, All Months, Total
Observations: 141,105) (Ref 1a)

having ceiling over 600 feet and visibility over 3 miles, but only a 99.7% chance of wind under 15 knots.

Data for surface winds at South Weymouth Naval Air Station,² one of the possible STOLport locations in the Boston area, has shown that the probabilities of crosswinds to given runway orientations can be approximated as normal distributions. However, noticeable deviations can be found from the assumed Gaussian distributions, and since a firm data base is available, a more detailed investigation of the data is in order. Figure 3.3-2 shows the assumed normal distribution, and the distribution based on the published data, for the entire 15-year period. The shaded area in the extremities of the latter distribution represents uncertainty due to the roughness of the published data. This figure shows that for a STOL aircraft to have a trip completion ratio of 99.5% or better at this airport, it would need a crosswind landing capability of at least 20 mph.

There are some correlations between meteorological conditions which are general characteristics, not limited to a particular location. For example, very low visibilities (less than 1/4 mile) are correlated with lower-than-average surface winds, even though there are certain conditions of low visibility (such as rain and snow) when winds can be expected to be high and gusty.³

3.3.2 Boundary Layer Shear

Associated with the mean surface wind is a boundary layer behavior near the ground, resulting in a decrease of horizontal wind velocity as the ground is approached. The wind shear (vertical gradient of horizontal velocity) in this layer may affect an aircraft during final approach. The thickness of the boundary layer, and hence the shear experienced by the aircraft, depends on the conditions of the flow — and especially the turbulence in this layer. When there is little turbulence, the boundary layer is so thin that only the smallest aircraft will experience any shear (although shear magnitudes are great). But when there is turbulence, the boundary layer thickens, and the layer extends high enough to affect the aircraft.⁴

In order to relate the shear to the turbulence, investigators have attempted to associate the shear with surface roughness or thermal atmospheric conditions. Both of these are representative of the amount of turbulence to be expected, and are more useful parameters than turbulence per se since they are more easily predicted. The dependence of the shear on surface roughness has been formulated⁵ with velocity assumed proportional to a power (p) of the height above ground. The proportionality constant is chosen to match the velocity to a constant mean wind above 1,000 feet (or some other reference altitude). A lower power p represents a

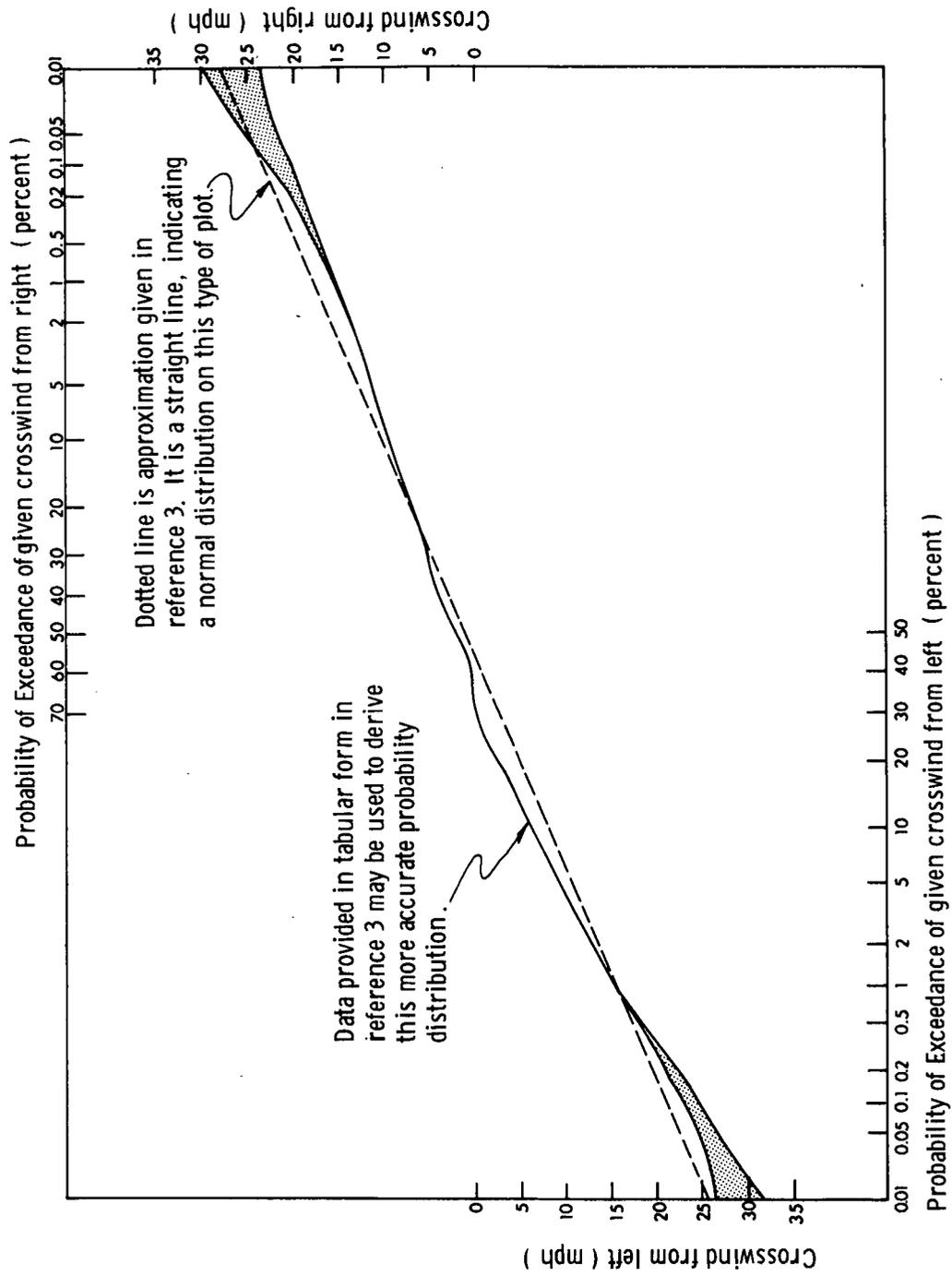


Figure 3.3-2 Probability of Exceedance of Crosswinds to Runway 15 at South Weymouth Naval Air Station, South Weymouth, Massachusetts

thinner boundary layer. The effect of surface roughness is included utilizing the "characteristic roughness length" of the terrain, a measure of the important length scale of the terrain irregularities. Wind velocity profiles have been found to agree fairly well with this model when p is equal to 0.12 for a roughness length of 0.3 cm (characteristic of an open airport), and with p varying up to 0.38 for a 5 m roughness (characteristic of a city). This model is consistent with the Weather Bureau's use of an exponent of 0.14 to scale measurements of airfield wind from actual measurement height to the standard measurement height of 30 feet.⁶

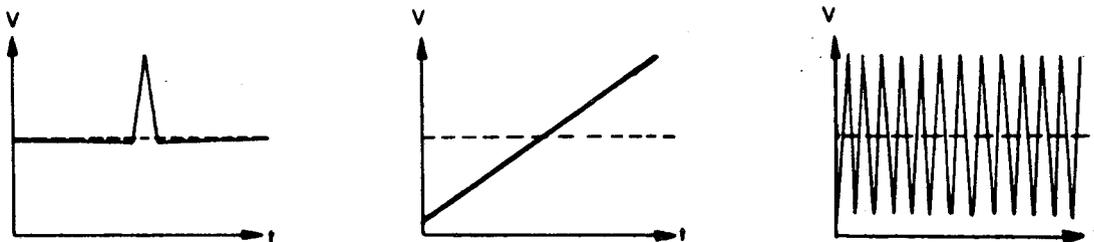
The dependence of the shear on thermal conditions is quite complicated, and will not be described here. The basic formula⁷ is valid only when the air is thermally unstable (usual on sunny days), though a modification is available for stable air.⁸

3.3.3 Turbulence and its Statistics

Turbulence is characterized by its random, and hence generally unpredictable, nature. It can therefore only be described in terms of expectations — that is, by its statistics. The form of the statistics used to describe any particular turbulent situation should be chosen with two guidelines in mind. First, the maximum amount of information should be used. Second, the form of the statistics should be convenient for use. The second stipulation may require that the first be modified slightly.

3.3.3.1 Methods of Statistical Representation

The statistical models used by different investigators do not always follow these general guidelines. For instance, some investigators have used the gust factor or gust coefficient, which is defined as the peak velocity measured in a time interval, divided by the average velocity in that interval. There has not been general agreement on what that interval should be,⁶ though 10 minutes appears to be used most often. However, this measure does not characterize turbulence well enough to evaluate its probable effect on an aircraft. All of the time histories shown below have the same gust factor and average velocity, but aircraft behavior would be markedly different for each one:



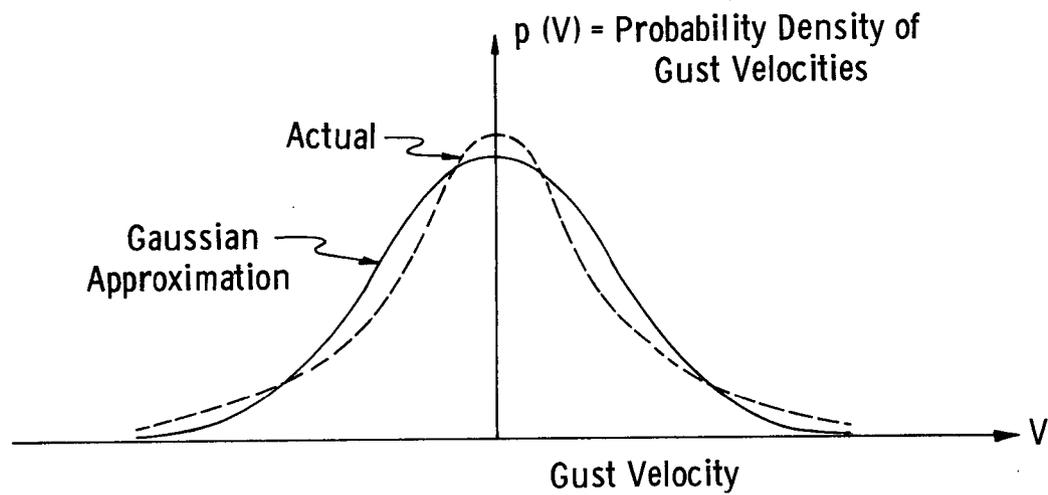


Figure 3.3-3 Comparison of the Actual Probability Distribution of Turbulence Velocities and a Gaussian Distribution

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3.3.3.2 Taylor's Hypothesis

The assumption known as Taylor's hypothesis greatly simplifies the statistical description of turbulence. It states that the magnitude and direction of turbulence velocities remain constant in a reference frame which floats downstream with the mean wind. The changes in turbulence velocities experienced by an aircraft are assumed to be due only to the motion of the aircraft through this turbulence field. This hypothesis is reasonable if the velocity variations seen by the airplane (due to the time change of the turbulence velocity at a given position) are very small compared with the variations due to its motion through the turbulence field. This hypothesis has been supported with only minor exceptions, none of which are very restrictive for the landing approach of a STOL aircraft.^{5,10,11} The exceptions include aircraft speed less than 1/3 of the mean wind speed (such as a hovering VTOL), and very low frequency turbulence.

When Taylor's hypothesis is assumed, the turbulence velocities must be considered as functions of space rather than time. This requires functional dependence of the PSD on wavelength, which is the inverse of the spatial frequency (or wave number), rather than on the period, which is the inverse of the time frequency. Thus, the PSD becomes the Fourier space-transform of the space-autocorrelation function. Spectra or autocorrelations may therefore be written in either the space or time domain, and one may be derived from the other when the space-time relationship is defined. An investigator may make measurements in an aircraft as time measurements and convert to space measurements, or he may make use of space measurements to predict the time function an aircraft will experience.

The only regime for which Taylor's hypothesis seems not to hold is for long wavelengths, especially of vertical velocity, at low altitude. This can become important over undulating terrain where, due to the flow caused by the mean wind, the vertical velocity field remains fixed to the terrain. An aircraft in these conditions would experience velocity variations, while a ground measurement station would find none. However, the hypothesis will not result in large errors when comparing turbulence experienced by aircraft travelling at speeds much higher than the mean wind speed.

3.3.3.3 Homogeneous Isotropic Turbulence

Turbulence at altitude (excluding what is known as clear air turbulence) is found to be well predicted by a homogeneous and isotropic Gaussian model. That is, the statistics of turbulence are not a function of position, and have no preferred direction. These properties are not surprising, since the turbulent energy originates

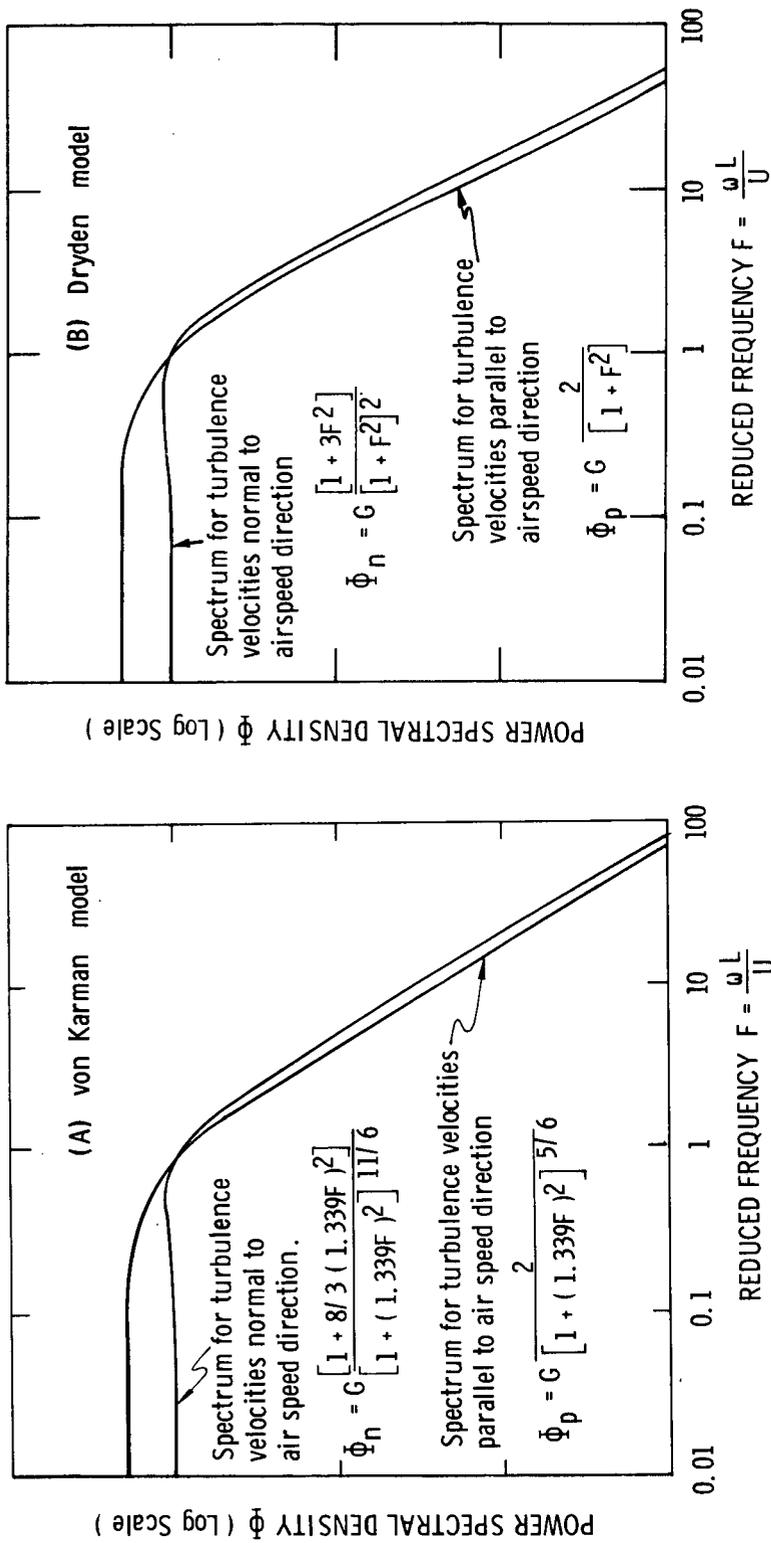
far from the point of measurement, and reaches the measurement point through a long process of atmospheric dynamics. These dynamics strongly filter the energy input; and the more that a random process is filtered, the more its statistics approach Gaussian. The isotropy results from the nature of the filtering: due to the presence of many eddies in the atmosphere, each eddy is rotated many times around random axes, and hence any original preferred direction is destroyed. As a result, the smaller eddies have more influence exerted on them by larger eddies and hence are filtered more — so the statistics of the shorter wavelengths are more Gaussian and isotropic than those of the longer wavelengths.

Although the assumption of isotropy includes the condition that the three components of velocity at a given position are not correlated, it should be noted that even in isotropic turbulence there are some important correlations of the space derivatives of those components. Derivations based on incompressibility and isotropy have shown a positive correlation between the variation across the wingspan of "headwind" turbulence velocity, and a velocity from the side occurring a characteristic time later.⁵ There is also a correlation of spanwise variation of side velocity, and a headwind velocity occurring later. These correlations affect the way in which an aircraft responds to turbulence, and may be important if the characteristic time involved is close to the characteristic time of an aircraft dynamic mode.

3.3.4 Modeling the Power Spectral Density at High Altitude

The behavior of the turbulence varies between different frequency ranges. The best understood of these is the inertial subrange, where wavelengths are larger than those for which viscous damping effects are of importance, but shorter than those at which turbulent energy originates. In this inertial subrange, there is no input or dissipation of energy, but nonlinear effects transfer energy from the longer wavelengths to the shorter wavelengths. Analysis of the dynamics for this subrange predicts that the power spectral density will vary as the $-5/3$ power of the frequency.¹² This $-5/3$ relation has been well verified by many experimenters.

In the inertial subrange, the power spectral density of longitudinal velocity is shown analytically to have $3/4$ of the magnitude of the lateral or vertical velocities (see Fig. 3.3-4). This is because of the difference in statistics of expected changes in velocity along the direction of that velocity, as compared with changes perpendicular to that velocity. This relationship of the spectral densities is derived using the assumptions of isotropy, incompressibility, and the $-5/3$ relation of the inertial subrange.¹³ Some experimenters have tentatively verified this $3/4$ relation, while others feel that the relation is more nearly one of equality.¹¹ A similar derivation may be performed for other frequency ranges, and will give the relationship between the spectra as a function of the local shape of the spectra.



where: ω = Frequency, U = Air speed, L = Characteristic length scale

Figure 3.3-4 Comparison of von Karman and Dryden Power Spectral Densities for Atmospheric Turbulence at Altitude

For wavelengths on the order of a centimeter, shorter than those of the inertial subrange, viscous effects become important and the turbulent energy is dissipated. Since these wavelengths are too small (and the corresponding frequencies too large) for them to affect an aircraft, the viscous subrange is not important to aircraft operators.

It is at frequencies less than that of the inertial subrange that turbulence energy originates, from such sources as mean wind flow over terrain features, and buoyant effects of thermally unstable air. Because of the great variety of meteorological conditions possible, which greatly affect the dynamics of the air in the low frequency range, the behavior in the energy subrange is not well predictable.

The von Karman power spectral density is found to be very representative of turbulence at altitude. The spectrum is shown in Fig. 3.3-4, and is specified by an amplitude and a characteristic length (or scale). The characteristic length specifies the "break frequency" separating the low frequency portion from the inertial subrange. For wavelengths much shorter than the characteristic length, the spectral density exhibits the $-5/3$ behavior expected of the inertial subrange. For wavelengths longer than the characteristic length, the spectrum is flat.

Because the $-5/3$ behavior cannot be represented by a polynomial power spectral density, many investigators have chosen instead to use an approximation which simplifies the resulting analysis by providing an integer slope of the inertial subrange. The most often used polynomial PSD is the Dryden spectrum which approximates the inertial subrange with a slope of -2 . The Dryden and von Karman spectra are presented in Fig. 3.3-4.

3.3.5 Behavior at Low Altitude

The homogeneous and isotropic assumptions for turbulence, which make some analytic results possible at altitude, break down within a few hundred feet of the ground. Thus, there is even less information about the turbulence near the ground than at altitude. For instance, the analytically derived slope of $-5/3$ for the inertial subrange, which has been so well established empirically at altitude, is theoretically valid only for homogeneous, isotropic turbulence. The nonhomogeneity affects the rigorous use of the PSD, but we will not concern ourselves with the modifications involved.

3.3.5.1 Anisotropy

As the ground is approached, the longer wavelengths (on the order of the height above the ground and longer) are modified by the ground effect, and isotropy breaks

down. Therefore, isotropy is generally considered to be a valid assumption for a wavelength-to-height ratio less than a "critical" ratio. Investigators have found that this critical ratio is about 1 in stable air, varying to as much as 10 in very unstable air.^{11,13-15} The high frequencies remain homogeneous and isotropic since they are still many wavelengths away from the ground, and hence do not feel its effect.

Because of the ground effect, the turbulence statistics must now be concerned with three distinct coordinate directions: vertical, since the ground physically damps the vertical velocities; downwind (along the mean wind), since the flow over the ground and the shear considerably affect the behavior; and crosswind. The velocities in these three directions are not even independent, due to the shear of downwind velocity. Although the crosswind component is uncorrelated with both the vertical and downwind components, these latter two components are correlated. This correlation is represented by the friction velocity u^* , which is the square root of the expected product of "downwind" and "down" turbulence velocities, and is predictable from the magnitude of the boundary layer shear.

3.3.5.2 Thermal Effects

The conditions of turbulence near the ground are very dependent upon the thermal stratification of the air layers near the ground, which may damp out or excite turbulence, and the boundary layer shear. The relative importance of these effects is represented by the Richardson number Ri , which relates the ratio of buoyant to mechanical (shear) forces.⁷ The expression is:

$$Ri = \frac{g(A + \partial T/\partial z)}{T(\partial V/\partial z)^2} \quad (3.3-1)$$

where g is the gravitational constant, T is temperature, V is horizontal velocity, and z is height. A (the adiabatic lapse rate) is a correction to the vertical gradient of temperature due to the fact that a rising parcel of air will expand and cool, due to lowering pressure, without any heat transfer to the surroundings. An atmosphere in complete equilibrium will have $\partial T/\partial z = -A$.

A positive Ri indicates that the buoyant forces are stabilizing, and an air mass with Ri greater than 0.25 is expected to have no turbulence. This is because air for this condition gets warmer with height. Therefore, any air that tends to rise will find itself among air that is warmer, and hence lighter, and so the original parcel of air will fall again. During conditions of very positive Ri , there may be a buoyant subrange between the energy and inertial subranges. In this buoyant subrange,

energy is dissipated due to the strong tendency of the atmosphere to damp any large-scale turbulent motions. The power spectral density may fall off as fast as the -3 power of the frequency in this subrange.

Conditions of negative Ri indicate buoyant instability, since the air decreases in temperature with altitude. A rising parcel of air will therefore find itself among air that is colder and hence heavier. The original parcel will then tend to continue to rise due to buoyant effects. The conditions of negative Ri will generally occur when sunlight is heating the ground, which in turn heats the layers of air near the ground. During conditions of low visibility (or at night), sunlight cannot warm the ground, resulting in a positive Ri . Turbulence, then, is negatively correlated with low visibilities and ceilings, though there are exceptional conditions such as thunderstorms.

The effects characterized by the Richardson number may not be very important for small parcels of air, where conduction of heat to surrounding air may reestablish the temperature of a parcel with respect to its surroundings. But it will hold for large parcels where conduction is not important. In addition, a small parcel displaced by its height will not experience nearly as much density difference with regard to its surrounding air, as will a large parcel displaced by its height. Thermal turbulence is therefore expected at low frequencies (long wavelengths) during conditions of thermal instability (negative Ri). Investigators have found definite convective (thermal) energy peaks for such conditions,^{14,15,16} mostly at wavelengths greater than 100 times the height for very low altitudes.

As shown in Fig. 3.3-1, the power spectral density is greatly modified by the conditions of thermal stability of the atmosphere. This modification takes place at lower frequencies than those associated with mechanical turbulence, which derives its energy from terrain roughness effects and shear in the boundary layer. The large energy peak possible due to convective effects, however, may not seriously affect the higher frequency portion of the spectral density (the inertial subrange) even though it may have many times the total power of the spectral density for stable air. This is true because the transfer of energy from lower to higher frequencies occurs by the same mechanism as it does in the inertial subrange, where the steady-state result is a PSD falling off as the $-5/3$ power of the frequency. Thus, the energy that the convective peak can feed into the inertial subrange is small compared with that fed in by the mechanical turbulence at much lower energy but at higher frequency. At lower altitudes both of these effects distinctly appear in the spectral density, and it will be necessary to include a convective turbulence peak in any low-altitude PSD model in order to represent the true nature of turbulence in unstable air. At altitude, the convective peak may have dissipated enough so that this is not required.

3.3.5.3 Similarity Hypotheses

Investigators are continually attempting to discover methods by which low-altitude spectra at different locations and altitudes and under different conditions may be compared, and by which spectra for new conditions can be predicted. To this end, investigators have attempted to determine the important similarity coordinates in which all spectra would be identical. These attempts have had very limited success.

For instance, the most commonly considered similarity hypothesis is that of Monin-Obukhov, which expresses the PSD-vs-frequency function in the similarity coordinates of "reduced PSD" and "reduced frequency". The reduced PSD is the PSD divided by the square of the friction velocity u^* , which is a measure of the shear in the boundary layer. The reduced frequency is the height divided by the wavelength. Although some investigators claim to have reached significant conclusions about the behavior of the spectral densities in the Monin-Obukhov similarity coordinates, more recent work has shown that this method works well for vertical but not horizontal velocities.^{13,14,15,17,18,19}

Other similarity coordinates have been proposed^{14,20} where the turbulence spectrum is not proportional to $(u^*)^2$, but rather to the square of the mean wind, U^2 , or even to $U^{1.6}$. Not only has the dependence on U^2 been found to work better than that on $(u^*)^2$ for the inertial subrange, but of course U is easier to measure than u^* . None of the similarity hypotheses, however, are very dependable.

3.3.5.4 Characteristic Length

Turbulence is generally described by its characteristic length, which is defined by different investigators in different ways. All of the definitions result in nearly the same measure, however. The characteristic lengths associated with the von Karman and Dryden spectra are shown in Fig. 3.3-4, and represent the break frequency beyond which is found the inertial subrange. The characteristic length is therefore the shortest wavelength at which substantial turbulence energy input occurs.

There are actually nine characteristic lengths of interest in low altitude turbulence. Each of the three velocity components requires three characteristic lengths to describe its variation in the three directions. Most investigators have measured autocorrelations (in order to estimate the characteristic length) from stationary towers, which measures the autocorrelations of the three velocities only in the downwind direction. In order to measure autocorrelations in the vertical direction, a number of sensors on the same tower is sufficient, and this has also been done.²¹ But very few investigators have established lines of instruments across the wind, or have flown aircraft at low altitude across the wind, to measure crosswind autocorrelations.

The available data on the vertical and crosswind statistics indicate that the scales of turbulence in the three directions are indeed different, but that the difference is not nearly as large as the difference in the scales of the three velocity components along any one direction. For instance, measurements at a height of 2 meters,¹⁰ where the differences can be expected to be more pronounced than at greater heights, have shown that the eddies of turbulence seem to be stretched in the downwind direction, so that the crosswind scale of any particular velocity component will always be shorter than the downwind scale. This effect is more pronounced in stable conditions, when the downwind scale may be as much as six times the crosswind scale, than in unstable air, when the downwind scale is only about 50% greater than the crosswind scale.

Measurements of the downwind scales of the three components of turbulence have been made by many investigators, and they have agreed on the major characteristics.²²⁻²⁶ Basically, the downwind scale of the vertical turbulence is approximately equal to the altitude for altitudes under 1,000 feet. For the horizontal components, the downwind scale does not go to zero at the ground (or if it does, it does so in a layer very close to the ground), but varies from about 500 feet at the ground to 1,000 feet at the 1,000-foot altitude. Because of the meager data available on crosswind and vertical scales of the three velocity components, these scales will be assumed equal to the downwind scales.

One investigator has stressed the dependence of the scales on the characteristic surface roughness length below about 300 feet, and on thermal stability above that altitude.²⁷ This dependence is expected due to the mechanical and thermal turbulence which depend in part on these factors, but the behavior is not known well enough to make good predictions of the scale variations.

These characteristic length scales do not provide full information about the autocorrelations, and provide no information about the cross-correlations relating two different velocity components. They do prove very useful, however, in formulating a model of turbulence when other information, such as the general shape of the power spectral density, is available. The turbulence scales given above will be assumed for neutral or slightly unstable conditions. For very stable conditions, buoyant effects would reduce the scales to as little as the characteristic roughness length. For very unstable conditions, the presence of the convective energy peak would greatly increase the scale.

3.3.5.5 Magnitudes of Turbulence Velocities

The magnitudes of the turbulent velocities, and hence the amplitudes of the power spectral densities, are represented by the rms values σ_u , σ_v , and σ_w (downwind,

crosswind, and vertical respectively). These are related to the spectral densities in that the mean-squared values (σ_u^2 , σ_v^2 , and σ_w^2) are proportional to the areas under the spectral density curves. The constant of proportionality depends on the units used, and on the form of the transforms between the frequency and space domains.

Experimental evidence has shown that the rms component of downwind velocity σ_u is generally equal to $0.2 U$, where U is the mean wind.²⁵ This is for slightly unstable conditions: it may increase due to the convective peak at very low frequency in unstable conditions.

The relation between the various components has been measured by many investigators with varying results.^{5,15,28} Taking an average of the available data, the ratio of $\sigma_u:\sigma_v:\sigma_w$ is about 1.0:0.7:0.5. These are the values near the ground, and σ_v and σ_w will increase with altitude so that all components are equal at about 500 feet. It should be noted that although σ_w halves as the altitude decreases from 500 feet to ground level, the characteristic length drops to zero. This results in much larger magnitudes of high-frequency vertical turbulence near the ground than at altitude.

There is also an important correlation between the "downwind" and "down" velocity components, which, as described previously, is represented by u^* . Experimental evidence has shown that the ratio of $\sigma_u:\sigma_w:u^*$ is about 1.0:0.5:0.35, so that the correlation coefficient $(u^*)^2/\sigma_u\sigma_w$ between the down and downwind velocities is about 0.25.^{5,15}

The values of σ_u , σ_v , σ_w , and u^* given above may be used, along with the length scales given in the previous section, to scale the von Karman spectrum to the conditions at low altitude. The Dryden spectrum may of course be used if computational simplicity is desired. However, these spectra will not be adequate models since, during conditions of strong thermal instability, a convective peak appears on the spectrum. Addition of this peak to the von Karman or Dryden spectrum forms a more suitable model. The peak should be added at a wavelength about 10 times the characteristic length of the unmodified spectrum, and should have a peak up to 10 times the value of the flat portion of the spectrum. A similar peak may be added if low-frequency vertical turbulence (due to mean wind flow over undulating terrain) is experienced by the aircraft near the landing field. The low frequency peak may not be very important for structural fatigue or passenger comfort, but it may have an important effect on following a planned flight path.

If there is interest in the variation of the strength of the turbulence due to unpredictable factors (or factors which are not taken into account here), this variation may be modeled by assuming the rms value of the downwind component, σ_u , to be a random variable, different for each landing approach. It has been suggested that a Rayleigh probability density function be used for this purpose.²²

3.3.6 Nonstationarity of Turbulence Experienced by Aircraft

The statistics of turbulence have been discussed in the framework of the power spectral density, because this representation is the most convenient for a stationary Gaussian random process. The spectral density has been used by investigators much more than the autocorrelation, which is the equivalent information in the time or space domain. The stationarity of the turbulence that has allowed use of the spectral density has depended on the measurement of the turbulence at a specific altitude, or at least within a small region. This has proven extremely useful in the characterization of the turbulence.

The aircraft, however, does not experience stationary turbulence statistics. The aircraft is continually losing altitude during the final approach, and therefore the characteristics of the turbulence (especially of the vertical velocity) are continually changing. In addition, it may be passing through various turbulent regimes that occur around the airfield, possibly due to changes in surface roughness. For the consideration of the effect of turbulence on the aircraft, then, the statistics can be reformulated from the space domain into the time domain of the moving aircraft. The power spectral densities are transformed into autocorrelations to be used in the nonstationary analysis.

The conversion of frequency statistics into a form suitable for analysis can be done for stationary statistics by designing a linear filter with white noise input such that its output has the spectral density required. For a linear filter with transfer function $F(s)$, the power spectral density of the output will be $F(s)F(-s)$. The state-space formulation of the linear filter is the form most suitable for the ensuing analysis. In the case of turbulence, assuming Taylor's hypothesis to hold, the spectral densities in the three orthogonal directions will be different, and consideration will have to be taken of the aircraft's flight path which will travel along each of the three axes at different rates — and possibly even at time-changing rates if the aircraft is maneuvering. The filter which produces the turbulence from white noise will, therefore, have to be a time-varying system.

3.3.7 Other Causes of Turbulence

There are various types of turbulence which do not follow the behavior described above. At high altitudes, these unusual occurrences are known as clear air turbulence, or CAT. Terrain features, large buildings, or even a row of trees may leave a shadow area downwind, in which the free wind velocity may be substantially reduced. The shadow area and free stream will be separated by a shear layer, in which strong turbulence is expected due to the unstable nature of the layer.^{4,8,29,30} A

large barrier therefore causes a double danger — strong shear and increased turbulence. These effects may be felt at downwind distances many times the size of the obstacle.

Generally, when there is an upwind change of characteristic surface roughness, there is an internal boundary layer (elevated shear layer) separating the air below (which is affected by the local roughness) from the air above (which is affected by the roughness found upstream). When the distance from the roughness change is large compared with the roughness lengths, the altitude of this internal boundary layer is about 1/10 of that distance.^{31,32} This internal boundary layer exhibits both shear and turbulence, as does that produced by a large obstacle.

The aircraft may also experience wake turbulence from other aircraft (or, under certain conditions, it may even fly into its own wake turbulence which it left behind some time ago!). This consideration is important when operating into airfields where conventional or jumbo jets operate. Even though current ATC practices tend to keep small aircraft away from very strong trailing vortices of other aircraft, moderate strength vortices may be experienced occasionally.

Another cause of turbulence is squalls, which are associated with thunderstorms. They may cause very large gust velocities with no warning.⁴

3.3.8 Conclusions

Although knowledge of turbulence near airfields is not very extensive, it is sufficient for establishing a reasonable model. This model should include all of the considerations mentioned throughout this section; including steady winds and wind shears, Gaussian turbulence, and internal boundary layers and their associated turbulence. The inclusion of the convective peak in the low-altitude turbulence model is very important for analysis of the aircraft's deviation from its planned flight path. It should be realized that this model, being Gaussian, does not consider the encounter of turbulence velocity magnitudes much larger than those usually expected: extreme velocities will occur more often than predicted by this model.

The von Karman or Dryden spectral density will be suitable for analysis of aircraft fatigue life and passenger comfort if it is augmented with the convective peak at low frequency. This convective peak should be placed with its maximum at a wavelength about 10 times the characteristic length of the spectrum, and should have an amplitude up to 10 times the low-frequency amplitude of the unaugmented spectrum, depending on the thermal instability of the atmosphere. The actual operating conditions of the aircraft should be considered in analyses of fatigue life and passenger comfort, since only a small portion of the aircraft flight regime will

be at low altitudes in strong turbulence. Thus, the fatigue damage will be correspondingly lessened. Also, the design goal for passenger comfort may allow for occasional exceedance of the preferred limits on accelerations.

More extensive information about turbulence would assist in improving the above turbulence model. Two types of studies would be helpful here: first, statistical studies of turbulence measurements near airfields; and second, further theoretical work and measurements designed to assist in the understanding of the basic physics of turbulence. The first approach is similar to that taken in Section 3.3.1 regarding steady winds, in which great masses of data were available and predictions of percentage occurrence of various conditions could be performed with little or no understanding of the physical processes involved. There, we were able to compute probabilities of exceedance of runway crosswind velocities based on over 100,000 observations taken hourly for fifteen years. This great mass of data included such information as ceiling and visibility in addition to wind information, which allowed investigations of important correlations of these parameters purely on statistical bases. There is probably a limit at which further data is not nearly as helpful as further theoretical studies — another 100,000 observations would hardly improve the information on winds, visibilities, and ceilings — but this limit is far from being reached in the field of turbulence at low altitudes.

Many parameters which are not of importance to aircraft response are of great importance in the understanding of the physical processes involved in turbulence. Therefore, careful planning is necessary if measurements taken for statistical studies are to be useful also for theoretical studies. For instance, the meteorological tower at Cape Kennedy measures only horizontal velocities since vertical velocities are not important in affecting a missile on a launch pad — but the lack of vertical velocity information has seriously hampered the use of the data in theoretical studies. Measurements taken for theoretical studies of low-altitude turbulence should ideally be done by a three-dimensional network of velocity and temperature sensors.

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3.4 APPROACH AND LANDING CONSIDERATIONS

This section describes a simple method of examining the approach and landing constraints on an aircraft approaching an MLS-equipped runway. We define the approach and landing phase of the mission to be that portion of the flight near the STOL strip where noise and obstacles become important considerations. Typical figures are roughly 5 miles from the strip and less than 2,000 feet above ground level. The ATC system, although of major importance in the terminal area, is of secondary importance during the landing phase. Airspace utilization, sequencing, etc., near the STOL strip can be taken into account under the heading of trajectory constraints. Constraints that are imposed on the operation of a STOL aircraft during the landing phase are:

- a. Obstacle and terrain clearance
- b. Allowable noise and pollution exposure
- c. Pilot workload
- d. Aircraft performance envelope
- e. Aircraft handling qualities
- f. Aircraft ride qualities
- g. Wind conditions
 - 1. Gusts
 - 2. Shear
 - 3. Crosswind
 - 4. Headwind
- h. Visibility
 - 1. Ceiling
 - 2. Range

3.4.1 Methodology

The proposed method of analysis is to specify the base and final approach legs of the terminal flight path by a small number of key parameters—the length of the final approach and the intercept angle of the base leg. The constraints imposed by guidance and navigation systems, aircraft performance, etc., can be plotted in the parameter space, yielding regions of allowable approaches. These plots may be used in two ways: (a) approach paths to any STOL strip can be designed to fall within the contours of allowable approaches as determined by the aircraft/avionics performance; or (b) the vehicle performance requirements can be determined for any given approach path.

The approach and landing phase is modeled as follows: a straight-line base leg followed by a constant-radius turn with rollout on final approach. The flight path angle will be assumed constant. The linear dimensions can be conveniently normalized with respect to the turn radius of the aircraft R (which must be greater than some value R_{\min}). Thus the approach is defined by the intercept angle i and the normalized approach distance d/R .

3.4.2 Preliminary Results

We now present some preliminary and partial results to indicate how the i - d/R parameter plane can be utilized. Consideration will be limited to the coverage given by the terminal landing aid, and the response of the guidance system (manual or automatic) to lateral errors at rollout on final. The turn onto final is assumed to start when the localizer beam is intercepted.

Landing Aid Coverage — The geometry of the localizer coverage is shown in Fig. 3.4-1: θ is the total beamwidth of the localizer (the localizer is assumed to be at a distance A beyond the touchdown point), y is the lateral displacement at the point where the beam is intercepted, and z is the longitudinal distance between the points of centerline acquisition and beam interception. The diagram derives the bound of $(d+A)/R$ to accomplish the approach for a given i

$$\frac{d}{R} \geq \frac{1 - \cos i}{\tan \frac{\theta}{2}} - \sin i \quad (3.4-1)$$

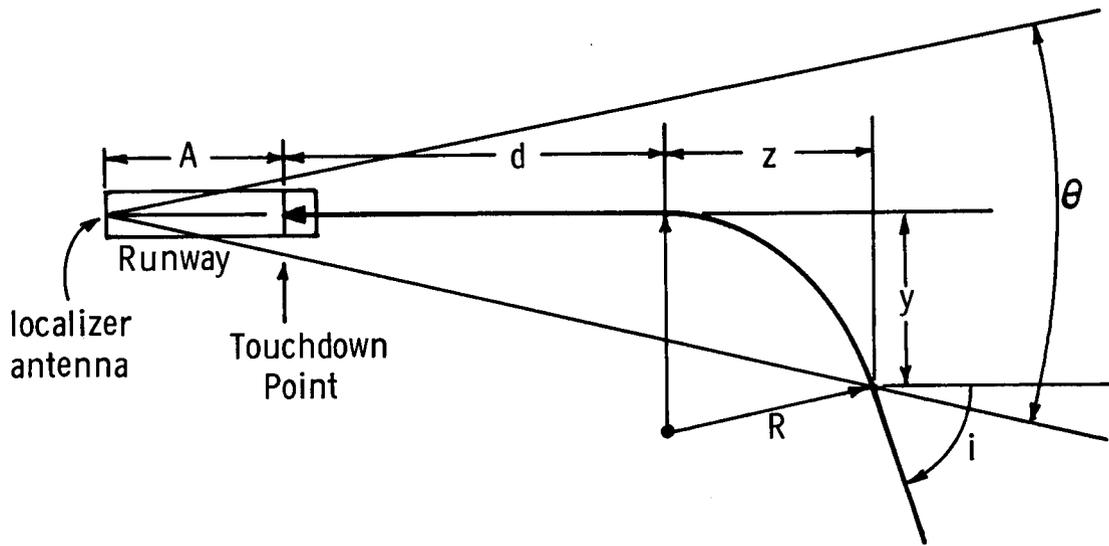
It can be shown that if

$$\frac{d}{R} \geq \frac{1}{\tan \frac{\theta}{4}} \quad (3.4-2)$$

then the entire circle lies inside the localizer coverage and an intercept of any angle can be made. This includes intercepts of greater than 360 deg which correspond to spiral approaches.

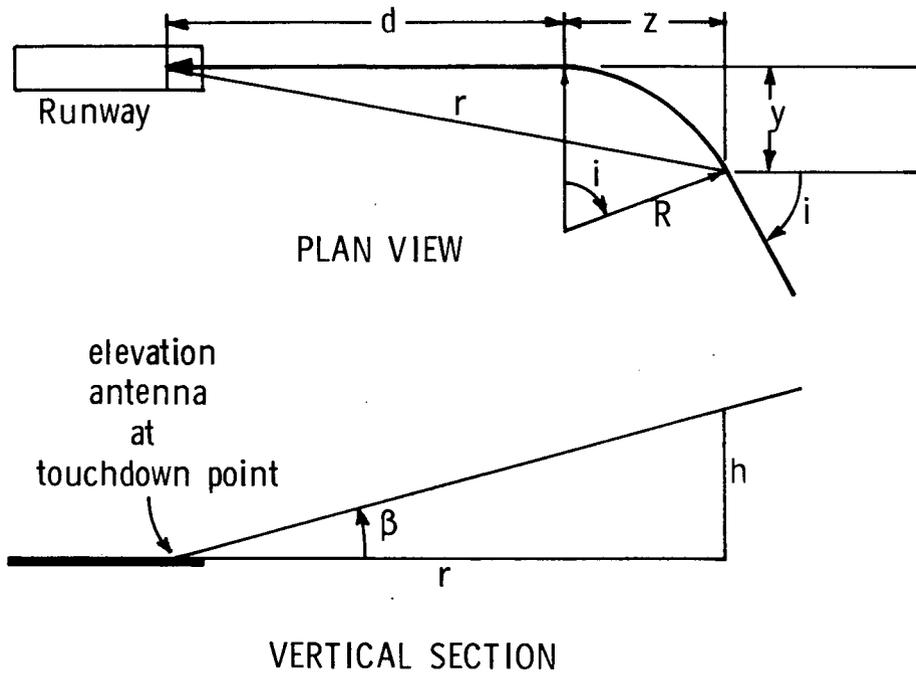
The geometry for elevation coverage is shown in Fig. 3.4-2, where β is the elevation angle. Assuming a constant flight path angle, γ , the expression for the elevation angle is

$$\tan \beta = \tan \gamma \frac{\frac{d}{R} + i}{\sqrt{\left(\frac{d}{R}\right)^2 + 2\left(\frac{d}{R}\right) \sin i + 2(1 - \cos i)}} \quad (3.4-3)$$



$$\left. \begin{aligned} \tan(\theta/2) &= \frac{y}{d + A + z} \\ y &= R (1 - \cos i) \\ z &= R \sin i \end{aligned} \right\} \quad \frac{d + A}{R} = \frac{1 - \cos i}{\tan(\theta/2)} - \sin i$$

Figure 3.4-1 Geometry of Localizer Coverage



$$\left. \begin{aligned}
 \beta &= \tan^{-1} (h/r) \\
 h &= (d + R i) \tan | \gamma | \\
 r &= \sqrt{(d + z)^2 + y^2} \\
 y &= R (1 - \cos i) \\
 z &= R \sin i
 \end{aligned} \right\} \beta = \tan^{-1} \frac{(d/R - i) \tan | \gamma |}{\sqrt{(d/R)^2 + 2(d/R) \sin i + 2(1 - \cos i)}}$$

Figure 3.4-2 Geometry of Glide Slope Coverage

Response to Guidance Errors — As a first (and admittedly optimistic) assessment of the constraints imposed by guidance errors we pose the following problem: given that the aircraft has rolled out from the turn onto final with the correct heading but a lateral displacement, what constraints are imposed by the requirement to return to the centerline with zero track error before reaching the landing aid?

Figure 3.4-3 shows that, neglecting the aircraft roll dynamics (an optimistic assumption), the following constraint must be satisfied if an initial error y_0 is to be nulled out using two turns of radius R in distance d .

$$\frac{d}{R} \geq \begin{cases} \sqrt{4 \frac{y_0}{R} - \left(\frac{y_0}{R}\right)^2} & \text{if } \frac{y_0}{R} < 2 \\ 2 & \text{if } \frac{y_0}{R} \geq 2 \end{cases} \quad (3.4-4)$$

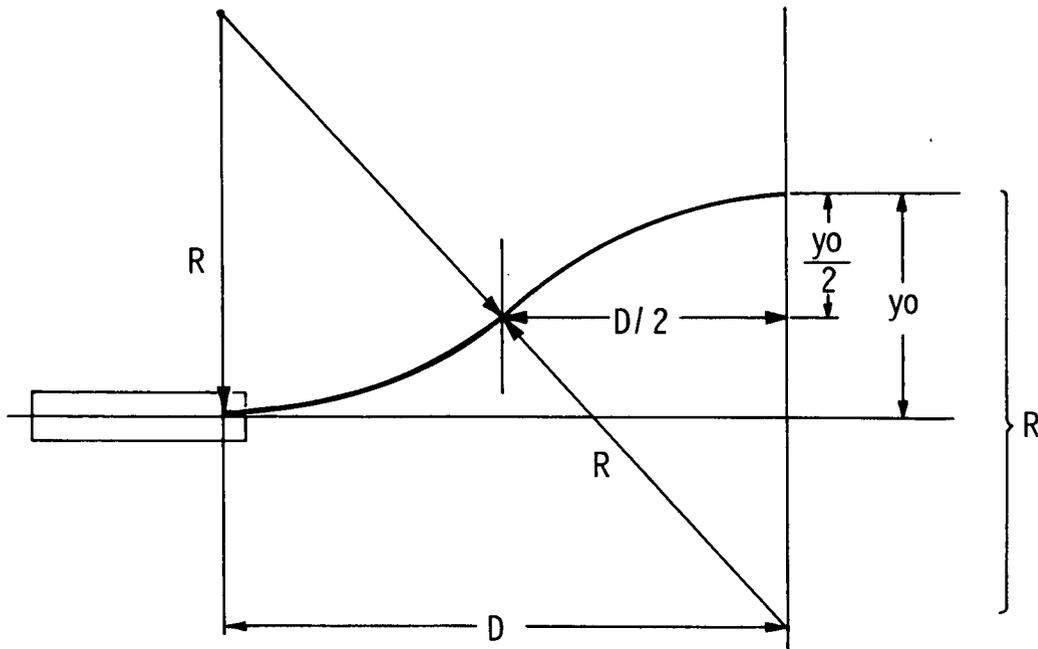
Because the assumptions were generous, we shall use the maximum lower bound, i.e., $d/R \geq 2$, to describe recovery from initial lateral errors.

This constraint is similar to the minimum-time-on-final required from the piloting viewpoint. To estimate this, assume that pilots require rollout to occur no later than the decision height. The decision heights for Category I and II conditions are 200 feet and 100 feet, respectively. For a glide slope of -7.5 deg this means that d should be greater than 1,500 feet and 750 feet for the two conditions. Thus we get the following bounds for d/R

R (ft)	$\frac{d}{R}$ (CAT I)	$\frac{d}{R}$ (CAT II)
500	≥ 3	≥ 1.5
750	≥ 2	≥ 1.0
1000	≥ 1.5	≥ 0.75

This constraint is on the order of the guidance error constraint.

Summary — The landing aid coverage requirements and recovery-from-lateral-error constraint are shown on the plots of Fig. 3.4-4. Two sets of curves are presented: the azimuth coverage curves (Fig. 3.4-4A) plot i vs $(d+A)/R$, taking into account the placement of the localizer transmitter at the far end of the runway, while the elevation angle coverage curves (Fig. 3.4-4B) plot i vs d/R since the elevation transmitter is located near the touchdown point.



y_0 = Initial Offset

D = Recovery Distance Using Two Constant-Radius Turns

$$\left(\frac{D}{2}\right)^2 = R^2 - \left(R - \frac{y_0}{2}\right)^2$$

$$D = \sqrt{4Ry_0 - y_0^2}$$

$$\frac{d}{R} \geq \frac{D}{R}$$

$$\frac{d}{R} \geq \sqrt{4\frac{y_0}{R} - \left(\frac{y_0}{R}\right)^2}$$

If $y_0 > 2R$, use two 90° turns

then, $\frac{d}{R} = 2$ becomes a lower bound

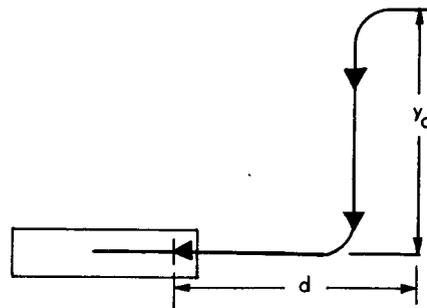
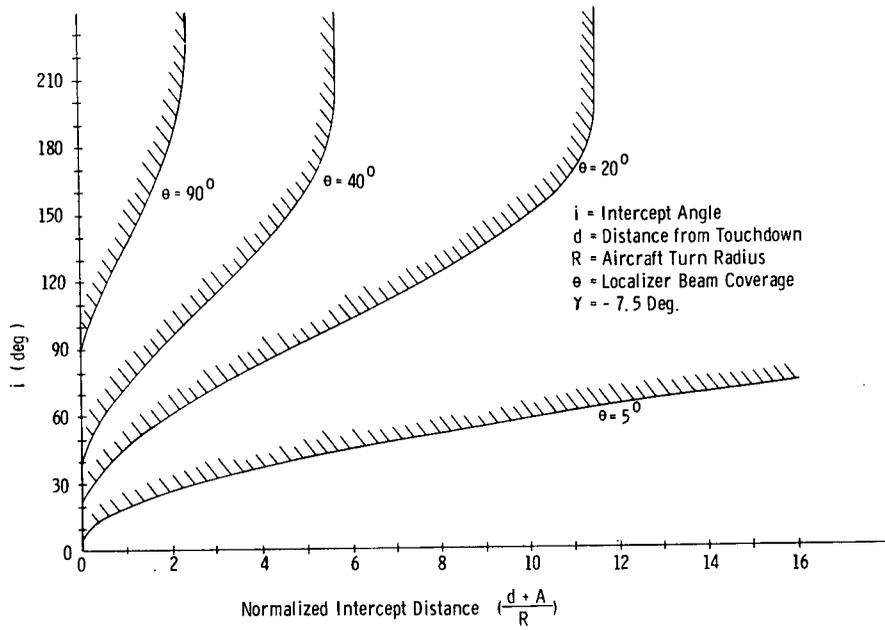
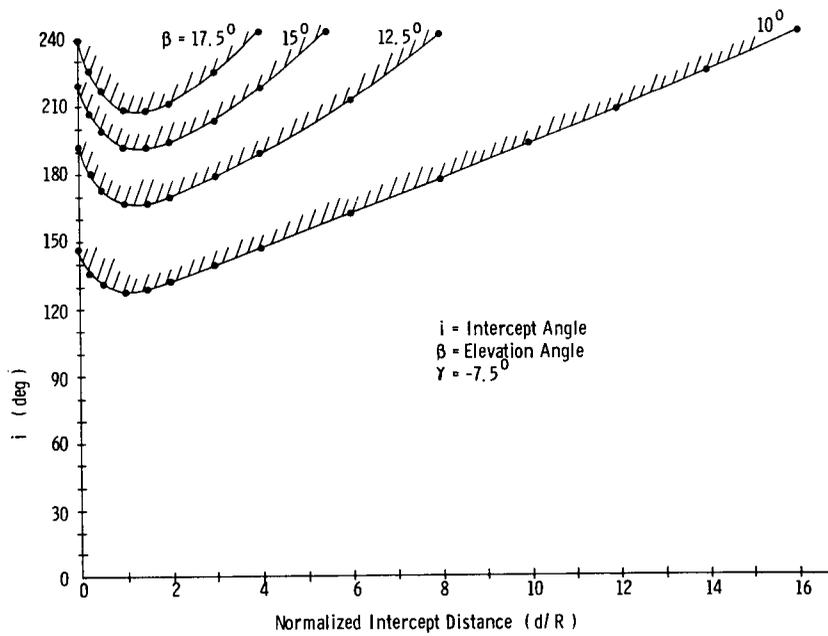


Figure 3.4-3 Recovery from Lateral Offset



(A) Localizer Beam Coverage Constraints



(B) Elevation Angle Constraint

Figure 3.4-4 Effect of Localizer and Glide Slope Coverage on Allowable Approach Flight Paths

It is seen that a wide range of approaches can be made with relatively modest elevation and localizer coverage. For example, assume $\gamma = -7.5$ deg, $A = 2,000$ feet, and $R = 550$ feet (60-knot approach speed with a 30-deg bank angle). For a final approach distance $(d+A)/R = 6.4$, and d of 1,500 feet (CAT I conditions), Fig. 3.4-4A shows that for a localizer coverage of only 20 deg, the intercept angle can be as high as 117 deg. If the localizer coverage is broadened to 40 deg, spiral approaches are possible, and the elevation coverage becomes the limiting factor. Looking at Fig. 3.4-4B with $d/R = 2.75$, we see that a 10-deg elevation coverage would be more than adequate for the 117-deg intercept corresponding to $\gamma = 20$ deg, while $\beta = 15$ deg would allow i to exceed 180 deg.

Looking at these plots from another viewpoint, if a 90-deg intercept angle is desired with a final approach distance d of 750 feet (CAT II conditions), and if the minimum turn radius is 870 feet ($V = 60$ knots, $\phi = 20$ deg) then the required localizer coverage is about 30 deg and the required elevation angle coverage is less than 10 deg.

3.4.3 Conclusions

The curves of Fig. 3.4-4 reflect the general trends for the simplifying assumptions used. More realistic conditions should be incorporated into the analysis, such as headwinds (which tend to decrease the requirements for d), crosswinds (which increase the recovery distance), a better estimate of minimum-time-on-final from a piloting viewpoint, etc. A more accurate model of aircraft dynamics and trajectory dispersions will lead to an improved estimate of the d/R necessary to null guidance and navigation errors after the turn onto final. The time delays associated with aircraft roll and heading rate response, pilot perception and reaction delays, receiver filter time constants, and ILS beam edge irregularities are very important factors that should be included, as a total delay of even 1 second produces large displacement errors. However, even with the crude assumptions made in this preliminary analysis, the curves provide insight into the important aspects of the approach geometry.

3.5 ATC SYSTEM INTERFACE

STOL operations within the context of the existing and evolving ATC system are the subject of this section. Operational procedures and problems are discussed, with emphasis on problem areas which might impact avionics and ground-system requirements.

Section 3.5.1 discusses runway capacity for STOL operations. STOL arrival capacity is found to be limited by separation requirements in the approach airspace. Analytical and queueing models are used to estimate arrival and departure capacity as a function of various separation standards and service times.

Section 3.5.2 is devoted to STOL operations at metropolitan jetports. The need for and desirability of such operations is discussed and methods for conducting such operations on a noninterfering basis are explored.

The final section, Section 3.5.3, examines terminal area airspace, STOLport, and suburban airport operations. Previous FAA simulation results and studies are reviewed and particular problem areas are identified.

3.5.1 Runway Capacity

The STOL demand levels discussed in Chapter 2 indicate that runway capacity may be a problem in certain of the larger demand centers. To determine if this is the case it is necessary to know the capacity of a runway or set of runways used for STOL operations. It is also necessary to know how capacity is affected by separation standards, regulations, and operational procedures, since these are in some cases subject to change.

Many excellent papers and reports have been written about airport and air traffic control system capacity,¹⁻⁴ but the subject is far from being well understood. Terminal area processes are exceedingly complex, and detailed analyses must deal with multiple, dependent, non-stationary, random variables or resort to simulation. In addition, it is often difficult to obtain measured data for comparison with theory. The present section will present the application of some simple analyses to STOL operations, draw some preliminary conclusions, and indicate where a more thorough analysis is needed and how it might proceed.

One is faced at the outset with the problem of defining what is meant by capacity. The maximum number of operations per hour which can be handled at an airport obviously varies with conditions; furthermore, as the airport operations rate approaches maximum, the arriving and departing aircraft are obliged to wait longer and longer periods of time on the average for the use of the facility. These facts

have led to the definition of a measure known as Practical Hourly Capacity (PHOCAP).²

Practical Hourly Capacity is defined as the maximum number of operations per hour which can be handled (steady state) at an airport under a prescribed set of conditions at a prescribed level of mean delay. It is difficult (though apparently possible⁵) to measure this quantity directly at an airport since conditions change rapidly, peak traffic periods are often of short duration, and certain components of aircraft delay (such as the delay to arrivals caused by path stretching) are not readily observable. Nevertheless, this quantity and methods by which it may be calculated are of considerable interest when the peak-hour behavior of the system is in question.

A measure which is often of more use to the airport planner is the Practical Annual Capacity (PANCAP).² Practical Annual Capacity is defined as the number of operations per year which can be handled at a given level of annual delay, given certain demand characteristics and runway usage assumptions.

In some applications, the time-dependent behavior of the system is of greater interest than the equilibrium behavior. Reference 3 discusses some analytical methods for dealing with this problem and explores periodic behavior in particular.

Before discussing the capacity of a STOL runway from the queueing point of view, we shall consider some simple deterministic and probabilistic models of the arrival process. These models serve to relate the sensitivity of the mean landing interval under capacity conditions to such factors as approach speed, traffic mix and ATC system performance.

3.5.1.1 Minimum Landing Intervals

There are in general two basic ATC safety requirements which impact on the minimum landing interval. The first is the requirement that the runway be clear of the preceding arrival (or departure) before the landing aircraft crosses the runway threshold and is committed to land.* The second is the requirement that IFR aircraft be separated by some minimum distance S , which is currently 3 n.mi. if radar separation procedures are in use and the aircraft are within 40 n.mi. of the radar installation.**

* The preceding aircraft need not have actually exited from the runway in all cases. See paragraph 560, Terminal Air Traffic Control.⁶

** Paragraph 1300, Terminal Air Traffic Control.⁶

For STOL aircraft using current IFR procedures, only the second requirement would affect the minimum landing interval, because runway occupancy times are short (on the order of 15 sec if adequate exits are provided), and approach speeds are slow. The minimum landing interval with a 3-n.mi. separation requirement and a 60-knot approach speed is 3 min. Reduced separation requirements may of course be adopted for STOL operations, but unless the time separation in the air approaches the runway occupancy time (which seems unlikely from the safety point of view), the general conclusion remains the same: the bottleneck is not the runway but instead, the approach airspace.

We shall not discuss separation requirements at the present time other than to point out the desirability and feasibility of reduced longitudinal spacing. The 3-min landing interval mentioned above results in a maximum of only 20 landings per hour. Other factors (traffic mix, queueing considerations, headwinds, etc.) would reduce this still further. From the reaction-time point of view, separation could certainly be reduced. A 1.5-n.mi. separation with a 60-knot approach speed results in a 90-sec time separation, more than adequate for controller/pilot communication and reaction.

It is interesting to examine the effect of the approach airspace bottleneck on the landing interval when the runway is used for aircraft of differing speeds. The situation is depicted in Fig. 3.5-1 and it is apparent that the minimum time separation T_{\min} at the runway threshold between a pair of aircraft having constant final-approach speeds V_1 and V_2 is given by

$$T_{\min} = \begin{cases} \frac{S}{V_2} & V_1 \leq V_2 \\ \frac{L}{V_2} - \frac{(L-S)}{V_1} & V_1 > V_2 \end{cases} \quad (3.5-1)$$

where L is the length of the final common path. When the first aircraft is slower than or equal in speed to the second aircraft, the second aircraft must be delayed before entering the gate such that the minimum separation occurs just as the first aircraft crosses the runway threshold. When the first aircraft is faster than the second aircraft, then the minimum separation occurs as the second aircraft is passing through the gate.

Assuming a mix of slow and fast aircraft (V_S and V_F respectively) then one finds four cases

$$T_{\min} = \begin{cases} \frac{S}{V_S} & V_1 = V_2 = V_S \\ \frac{S}{V_F} & V_1 = V_2 = V_F \\ \frac{S}{V_F} & V_1 = V_S, V_2 = V_F \\ \frac{L}{V_S} - \frac{(L-S)}{V_F} & V_1 = V_F, V_2 = V_S \end{cases} \quad (3.5-2)$$

If one now assumes that slow and fast aircraft arrive in random order with probabilities p_S and p_F respectively, then the average separation is just

$$E[T_{\min}] = p_S^2 S/V_S + p_F^2 S/V_F + p_S p_F \left[\frac{L}{V_S} - \frac{(L-2S)}{V_F} \right] \quad (3.5-3)$$

where

$$p_S + p_F = 1$$

The effect on maximum arrival rate of a STOL/CTOL mix for various values of L is shown in Fig. 3.5-2. A separation requirement of 3 n.mi. was assumed, along with approach speeds of 60 and 140 knots respectively. Even a small percentage of STOL traffic in the arrival stream is seen to greatly reduce the arrival rate. This is caused mainly by the low STOL-only arrival rate, but it is seen that a further degradation occurs as the length of the final common path is increased. This is an example of the so-called "funnel effect" which was first investigated systematically by Blumstein.⁷

Let us now turn to the effect of ATC system performance on minimum landing intervals.⁸ Figure 3.5-3 shows a situation in which aircraft fly the same final-approach speed V . The task of the ATC system in this example is to deliver the aircraft to the approach gate as closely spaced as possible without violating the minimum separation requirement very often, say less than 0.1% of the time. In order to accomplish this task when the ATC system is unable to deliver aircraft to the gate at precisely the times required, it is necessary to increase the mean separation above the minimum as shown in the figure. To keep the illustration simple, assume that the probability density function of the time separation t of the two aircraft when the second reaches the gate is given by

$$p(t) = \frac{1}{\sqrt{2\pi} \sigma} e^{-\frac{(t-\bar{t})^2}{2\sigma^2}} \quad (3.5-4)$$

where \bar{t} is the mean time separation and σ is the standard deviation. The probability of a spacing violation is given by the following integral which must be set equal to 0.001:

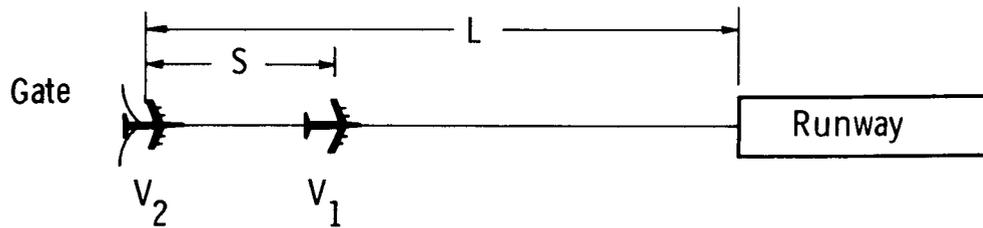


Figure 3.5-1 Separation Requirements in the Approach Airspace

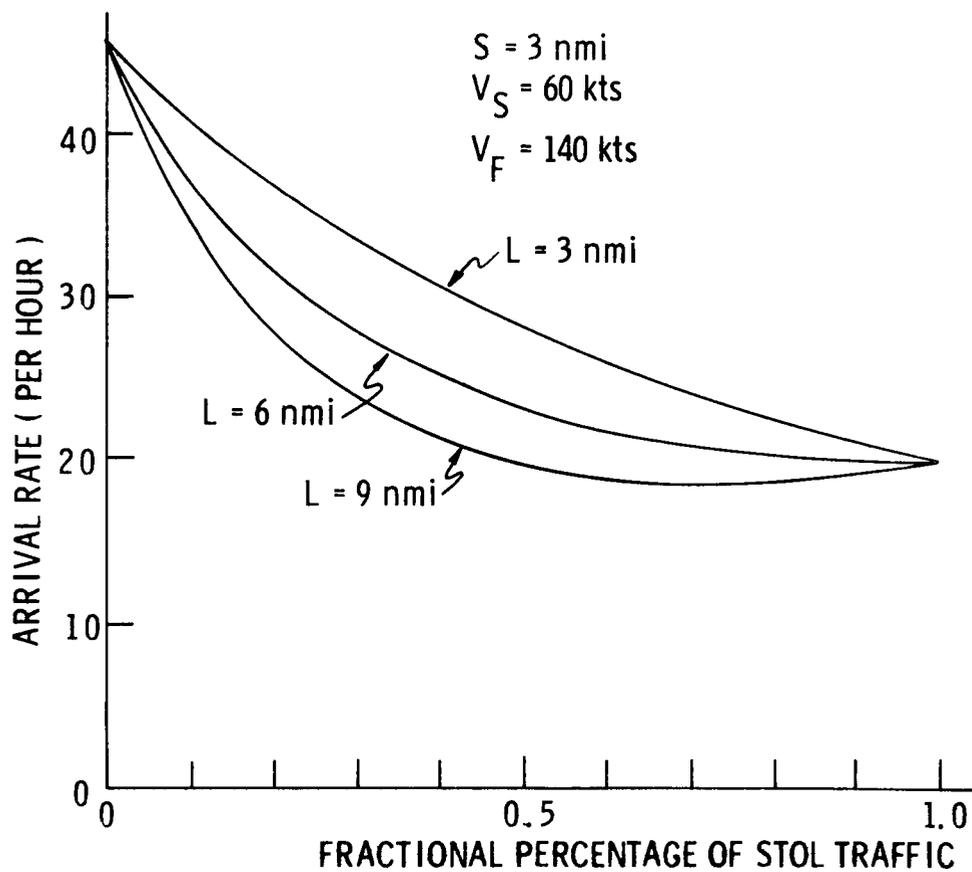


Figure 3.5-2 Maximum Arrival Rate as a Function of the Fractional Percentage of STOL Traffic

$$\frac{1}{\sqrt{2\pi} \sigma} \int_{-\infty}^{S/V} e^{-\frac{(t-\bar{t})^2}{2\sigma^2}} dt = 0.001 \quad (3.5-5)$$

From the standard tables for the values of the integral, one finds

$$(\bar{t} - S/V)/\sigma = 3.09 \quad (3.5-6)$$

Therefore, the mean separation is given by

$$\bar{t} = 3.09\sigma + S/V \quad (3.5-7)$$

The maximum arrival rate implied by this mean separation for STOL approach speeds ($V=60$ knots) is shown in Fig. 3.5-4 as a function of ATC system delivery accuracy σ and the separation requirement S .

It should be noted in passing that ATC delivery accuracy would be a function of STOL navigation capabilities if 4-D RNAV equipment and approach procedures were developed and in use.

The above analysis has assumed that a traffic controller or an automated ATC system would increase the mean separation to account for errors in delivery of the aircraft to the approach gate. A more complete analysis would have to account for these errors in greater detail and consider in addition the effect of winds and variations in final-approach speed on the probability of separation violation. Some work along these lines has already been done.⁹

We turn now to a discussion of queueing theory as applied to runway capacity determinations.

3.5.1.2 Queueing Considerations

A runway can be regarded as a service facility. It can be used by only one aircraft at a time (arrival or departure), and other aircraft seeking to use it must be delayed until it is free. When the runway occupancy time for arrivals is very small, then separation requirements in the approach airspace limit the minimum landing intervals, as we have observed. In this case, arriving aircraft must queue for use of the approach airspace as well as the runway, and the approach airspace can also be regarded as a service facility. Queueing theory can be used to derive information about the number of aircraft in the queue and the delays which they experience.

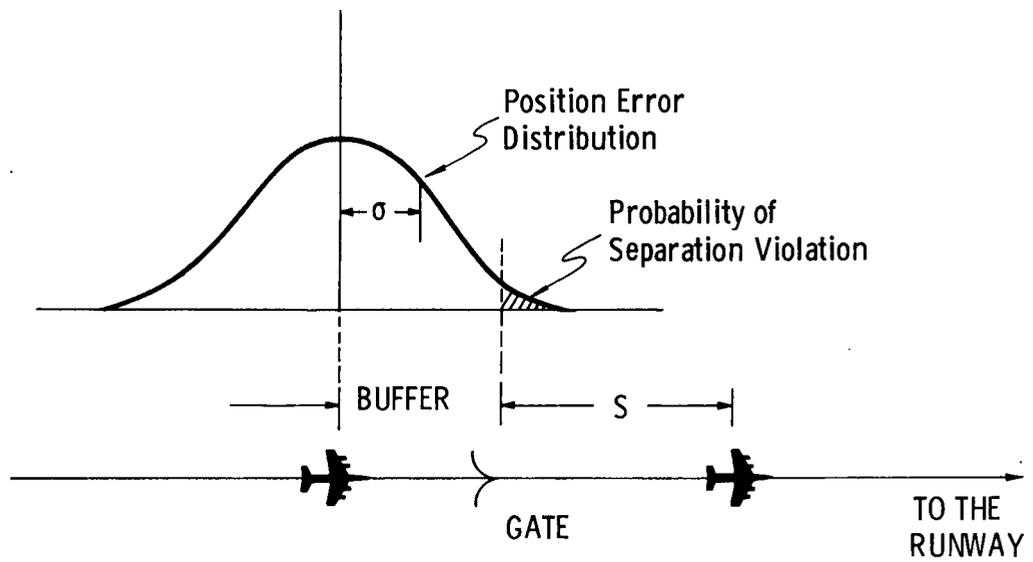


Figure 3.5-3 The Effect of ATC System Delivery Accuracy on Separation at the Approach Gate

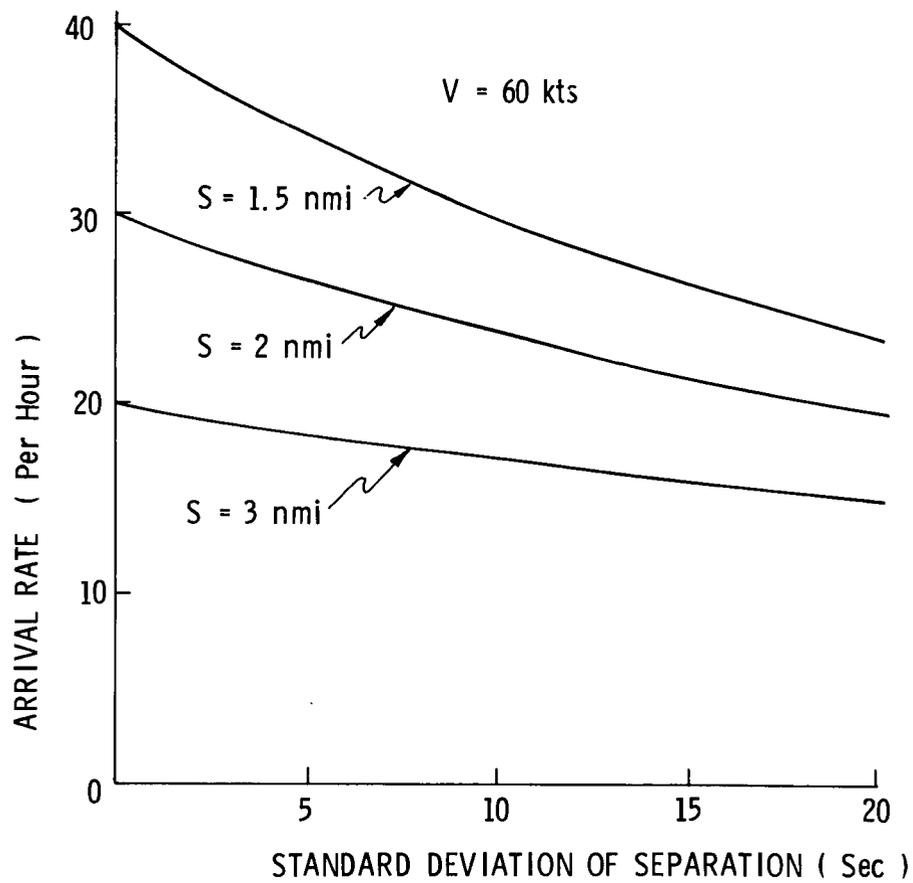


Figure 3.5-4 Arrival Rate as a Function of ATC System Delivery Accuracy and Separation Requirement

In the usual queueing situation, assumptions are made concerning the statistics of the input process and the service process and then the queue statistics are calculated. Let us assume for the sake of mathematical convenience that arrivals into the terminal area are Poisson distributed; that is, that the probability that n aircraft arrive in a time interval of length t is given by

$$p(n;t) = e^{-\lambda t} (\lambda t)^n / n! \quad (3.5-8)$$

where λ is the mean arrival rate (assumed constant). The probability density function p_i of the interarrival intervals τ for such a process can be shown to be the exponential distribution

$$p_i(\tau) = \begin{cases} \lambda e^{-\lambda \tau} & \tau \geq 0 \\ 0 & \tau < 0 \end{cases} \quad (3.5-9)$$

Let us now characterize the airspace in the vicinity of the approach gate as a service facility. After an aircraft passes through the gate, a period of time A must elapse before the next aircraft can enter. Arriving aircraft pass through the gate as soon as it becomes free in a first-come, first-served manner. If no aircraft is ready to enter when the gate becomes free, then the facility is said to be "unoccupied" until the next arrival. In order to define the statistics of the service process completely, it is necessary to specify the probability density function for the service times A .

If the service times are statistically independent, then it can be shown that the mean value of the arrival delay W is the following function of the first two moments of the service-time distribution:

$$E[W] = \frac{\lambda E[A^2]}{2(1 - \lambda E[A])} \quad (3.5-10)$$

This equation, which can be written in many forms, is known as the Pollaczek-Khintchine formula.

Let us suppose that the aircraft approach with constant velocity V and that a minimum separation S is required. The service time in this case is just the constant value S/V . The mean arrival delay as calculated using the Pollaczek-Khintchine formula is shown in Fig. 3.5-5 for an approach speed of 60 knots and various separation requirements. As can be seen, the arrival delay is a rapidly increasing

function of the arrival rate. Furthermore, the hourly capacity at a reasonable level of mean delay (2 min, for example) is much less than the rate which might be inferred by taking the reciprocal of the minimum interarrival time.

The Pollaczek-Khintchine formula is one of the basic results used to determine the arrival capacity of an airport.^{2,5} A semi-empirical procedure is used. The interarrival intervals (identified with the service times) for aircraft pairs of various types are measured under both visual and instrument weather conditions. The formula is then used to find the arrival rate corresponding to a given level of delay (4 min for air carrier airports) for a given weather situation and mixture of traffic. The resulting arrival rates (one for visual and one for instrument weather conditions) are referred to as the visual or instrument Practical Hourly Capacities for arrivals at that airport. Measurements of actual delay to arrivals (time spent in holding patterns) verify that this procedure gives reasonably accurate results, even though certain of the assumptions might be difficult to justify on a theoretical basis.⁵

When a runway is used for both arrivals and departures, the situation becomes considerably more complicated. Departure aircraft form a second queue for runway usage, and the characteristics of this queue must be examined. Present ATC procedures give landing aircraft priority over departures, a practice which can lead to long departure queues and delays. Long departure queues could not be accommodated at a small STOLport, thus investigation of the arrival/departure process becomes particularly pertinent.

Present runway arrival/departure capacity analyses proceed in a similar fashion to that indicated above for arrival capacity.⁵ Inputs to the departure process are assumed to be Poisson distributed. The interarrival intervals at the runway threshold are assumed to be made up of a minimum interval B (representing the time during which the landing aircraft is committed to land or is actually occupying the runway) and an exponentially-distributed gap interval G. Arrivals are assumed to have priority over departures, which means that the departures must be held during B, but can be released if the interval G is large enough.

The equilibrium departure delay W_D can be explicitly calculated for these circumstances, although the formula is complex and will not be repeated here (see Ref. 5). Functionally, it can be represented as

$$W_D = W_D \hat{\alpha}_A, \lambda_D, B, F, T) \quad (3.5-11)$$

where the symbols have the following meanings:

- λ_A - arrival rate;
- λ_D - departure rate;
- B - the mean runway occupancy time plus a small additional interval during which the aircraft is committed to land;
- F - mean time required for the release of a departure in front of an oncoming arrival;
- T - mean time required between departures.

The departure capacity of the runway used for mixed operations is found using a procedure similar to that described above for arrival capacity. The only differences are that there are now three variables to be measured (B, F, and T), and that it is necessary to specify the arrival/departure ratio (the ratio of the arrival rate to the departure rate) which would normally be unity. It usually turns out that the departure capacity of the runway is somewhat less than the arrival capacity referenced to the same level of delay. This might be expected in view of the priority given to arrivals.

To calculate the Practical Hourly Capacity of the runway used for mixed operations, it is necessary to know both the arrival capacity and the departure capacity. If the arrival/departure ratio is unity, then the Practical Hourly Capacity is defined to be twice that of the lower capacity of the two streams of traffic. In the normal case when the departure capacity is less than the arrival capacity, the runway is said to be "departure-limited."

Once again, the departure delay calculated using the above procedure has been found to correspond well to measured data.

It is interesting to consider an example of departure delay calculated using the formula of Ref. 5. Let us make the following assumptions: the arrival/departure ratio is unity, the interval B is essentially the runway occupancy time for STOL (taken to be 15 sec), the interval F is given by D/V where D is the distance separation required before a departure may be released in the face of an oncoming arrival, V is the approach speed (taken to be 60 knots), and the interval T is 60 sec as per current regulation. In summary:

- $\lambda_A = \lambda_D$
- B = 15 sec
- F = $D/(60 \text{ knots})$
- T = 60 sec

Figure 3.5-6 shows the resulting departure delay as a function of operations rate for various values of D. The required arrival/departure separation is currently 2 n.mi.; using that value of D one finds that approximately 32 operations per hour (steady state) will result in a mean departure delay of 2 min. Referring to Fig. 3.5-5, one finds that the mean arrival delay at an operations rate of 16 arrivals per hour (half of the operations rate) for the current arrival separation standard of 3 n.mi. is greatly in excess of 2 min. On this basis it would appear that for current separation standards, landing priority rules, and STOL-like approach speeds and runway occupancy times, the runway capacity is arrival-limited and would be approximately 23 operations per hour for a mean arrival delay of 2 min.

In the normal airport situation, runway capacity is departure-limited as mentioned above. In the STOL situation, the opposite result comes about because the low STOL approach speed combined with short STOL runway occupancy time provide ample opportunities for the release of departures. This would not necessarily be the case should other combinations of separation standards S and D be adopted. For example, if S is reduced to 1.5 n.mi. and D to 1 n.mi., a situation results in which the runway capacity is departure-limited (though not excessively so) with an operations rate of 52 operations per hour at the 2-min departure-delay level.

Figures 3.5-5 and 3.5-6 can be used to explore the dependence of STOL runway capacity on values of the separation standards S and D for the given values of B and T. For other cases, the actual formulas for computing delay must be used.

3.5.1.3 Conclusions and Future Work

In order to minimize the cost and disruptive impact of STOL operations within the ATC system, it is desirable to limit specialized procedures and regulations to only those deemed most essential to the success of the venture. From the runway capacity point of view, it would appear that special reduced separation regulations are essential for STOL. The Practical Hourly Capacity under present standards for mixed operations on the STOL runway at a mean arrival delay of 2 min is only 23 operations per hour (half arrivals and half departures). If the required arrival/arrival separation is reduced from 3 n.mi. to 1.5 n.mi. and the arrival/departure separation from 2 n.mi. to 1 n.mi., then the Practical Hourly Capacity becomes 52 operations per hour.

In addition to being strongly affected by separation standards, the maximum arrival rate at the runway depends on such factors as the mix of traffic, the length of the final common path, and the ability of the ATC system to deliver aircraft to the approach gate accurately. A simple calculation shows that even a small percentage of STOL traffic in a CTOL traffic stream dramatically reduces the arrival rate (Fig. 3.5-2).

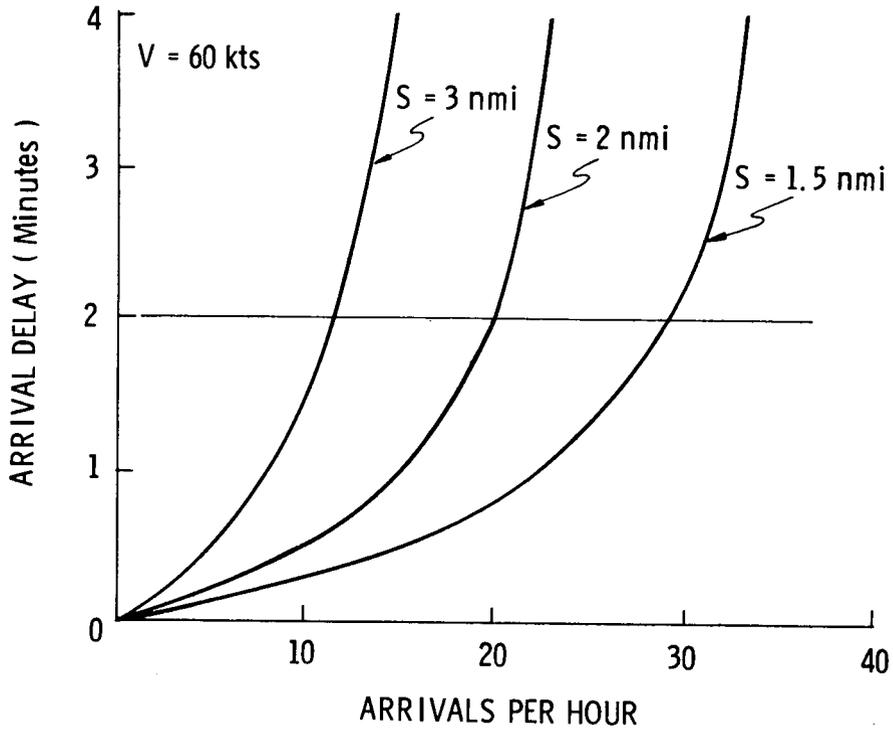


Figure 3.5-5 Arrival Delay as a Function of Runway Arrival Rate

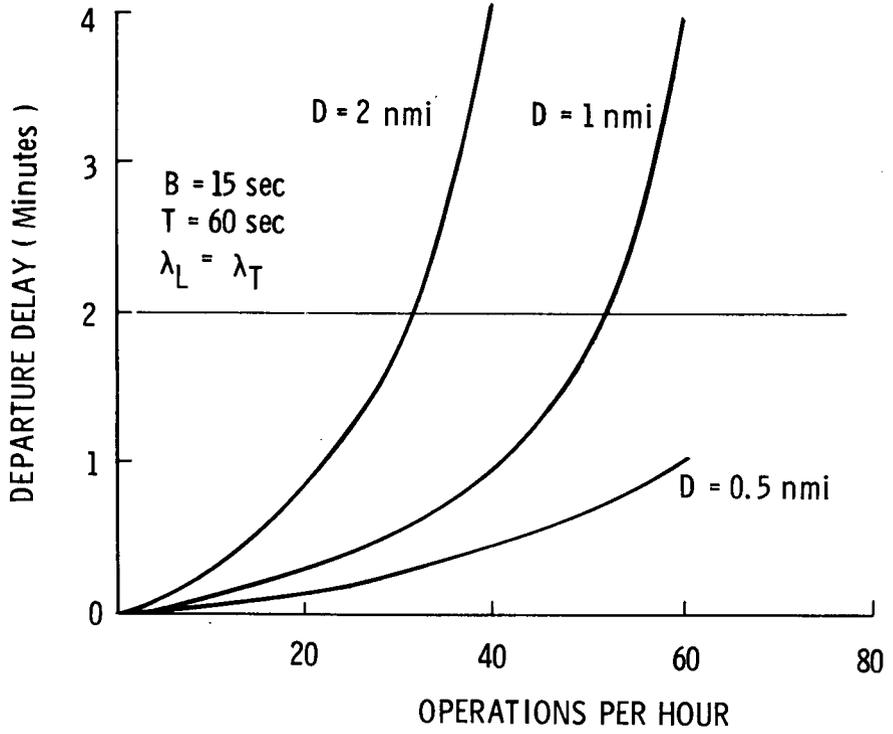


Figure 3.5-6 Departure Delay as a Function of Runway Operations Rate

The above discussion has focused on peak-hour delays as a means of specifying the level of service provided as a function of operations rate. A 2-min mean delay level has arbitrarily been selected as a capacity reference. One of the important areas for future work is to determine an acceptable level of delay for STOL. STOL transportation systems are shown to be economically feasible or infeasible on the basis of trip times and costs, both of which increase with increased terminal area delays. Future economic studies should include the effects of congestion and terminal area delays in the analysis.

The time-varying behavior of the delay process for STOL should be examined along the lines suggested in Ref. 3.

The equilibrium delay formulas cited in this section are of limited usefulness in certain respects and an effort should be made to improve them. The formulas depend on a number of simplifying assumptions which might be questioned. Such assumptions include the identification of interarrival times with arrival service times, the assumption that service times are constant, that they are independent, and so forth. The justification for the assumptions is that the formulas work. Measured delays are in reasonable agreement with those predicted. The difficulty arises when one wishes to apply these semi-empirical formulas to a new situation (STOL operations) where measured data is not yet available. Some work is needed to determine how well the formulas work in this new situation. Simulation data would be most useful here.

In addition to reducing separation standards, it may be desirable to alter the arrival-priority rule for the use of the runway. Equilibrium formulas for the departure delay for other priority rules should be derived where necessary and examined for the case of STOL operations. The practicality of using alternative priority rules should also be examined. STOLport simulation results¹¹ have indicated substantial reduction in overall delay through use of a priority rule which alternates arrivals and departures when there are aircraft in both queues.

The application of capacity analysis to the case of STOL/CTOL operations on separate runways at major jetports is an area of importance for future work. Some general considerations relating to STOL operations at jetports are given in the next section.

Finally, the need for empirical data on STOL runway service times and delays should be emphasized. Real-time ATC simulations can be used here, as can flight-test data on runway occupancy times for arrivals and departures, pilot reaction times, and the like.

3.5.2 STOL Operations at Metropolitan Jetports

Although there are many reasons why one would want to implement an independent STOL transportation system operating in a congestion-free fashion from centrally-located STOLports, the need for or desirability of STOL operations at metropolitan jetports is less clear. In fact, the CAB in its Northeast Corridor VTOL Investigation (see Section 2.2) ruled out such operations for the purposes of their study. This was done presumably to ensure that the intercity V/STOL system would help alleviate congestion at major jetports and not contribute to it.

Nevertheless, it may not be practical to completely rule out the use of jetports by an intercity STOL service. STOLports will be expensive, so it makes sense to use existing facilities wherever possible. Furthermore, the economics of air transportation may dictate that STOL flights connect with existing CTOL flights (both long-haul and short-haul) to satisfy the needs of the travelling public. Finally, there may be no other choice. It may not be possible to find a suitable site for a STOLport because of competing land use or because of the general community reaction against any airport development.

Furthermore, it may actually be desirable from an airport-capacity point of view to have STOL operations at the jetport. The STOL vehicles may be able to utilize runway facilities not usable by conventional aircraft due to noise-abatement restrictions, runway-length limitations, or obstacle-clearance problems. The key issue is whether safe, reliable STOL operations can be conducted without interfering with CTOL operations.

This section will examine various methods for conducting STOL operations at metropolitan jetports to see whether such operations can be implemented on a noninterfering basis. Avionics and ground-system requirements are discussed briefly, and some suggestions are made regarding the analysis of system capacity and safety.

Let us first examine the various types of STOL services which might exist at metropolitan jetports. Two possibilities must be considered: STOL operations between a STOLport and a jetport and STOL operations between two jetports.

3.5.2.1 STOLport/Jetport Services

Referring to Fig. 3.5-7 we see that there are basically three types of STOLport/Jetport services: intercity, feeder, and third level operations. Considering intercity STOL service first, STOL aircraft would operate between jetport J1 located in city No. 1 and STOLport S2 located in city No. 2. This service would provide fast, convenient transportation between the two cities by locating the STOLport

closer to the demand center and by avoiding the air traffic congestion and the consequent delays encountered at J2. STOL service would also relieve some of the congestion at J2 by siphoning off part of the short-haul traffic between 1 and 2. STOL characteristics would be required at one end of the line but might not be needed at J1. A feeder service would be required from the STOLport to J2 to connect the STOL network with the CTOL network, or simply to provide a downtown/crosstown air service. This feeder service could be either STOL or VTOL. Third level STOL service as depicted is already in existence utilizing Twin Otter aircraft.

3.5.2.2 Jetport/Jetport Services

Two types of service can be identified for Jetport/Jetport operations as illustrated in Fig. 3.5-8. The first is an air shuttle service between two neighboring jetports. To make this operation feasible, direct routing between the two facilities would be provided. Conventional aircraft would not be used because of the short stage lengths involved.

The second type of operation is the supplementary intercity STOL service between two more-distant jetports, one or both of which is operating near peak capacity. Any increase in capacity would require the construction of another jetport, more runways, or the use of larger aircraft. None of these solutions may be feasible for the area in question. An alternative solution would be to use STOL aircraft operating in parallel with the conventional aircraft. The airport may have adequate ground space to permit simultaneous operations, but because of noise-abatement restrictions, runway-length limitations, or obstacle-clearance problems, the available facilities cannot be used by conventional aircraft. Thus a STOL aircraft with a smaller noise footprint, short landing distance, and steep approach capability may be able to utilize these existing facilities. The airport may have actual or planned STOL runways (Fig. 3.5-9 shows existing and planned STOL runways at Boston's Logan International). To achieve the maximum benefit in this situation, the STOL vehicles should have a large passenger-carrying ability, and the STOL runways should be located so as to minimize STOL/CTOL conflicts.

3.5.2.3 STOL Operational Procedures at Jetports

Now that we have identified some of the reasons for STOL operations at jetports, let us look at some possible operational procedures. Three broad categories of STOL/CTOL procedures will be discussed. These are STOL/CTOL operations on the same runway, on intersecting runways, and on parallel runways. The possibilities for noninterfering or capacity-enhancing operations will be explored.

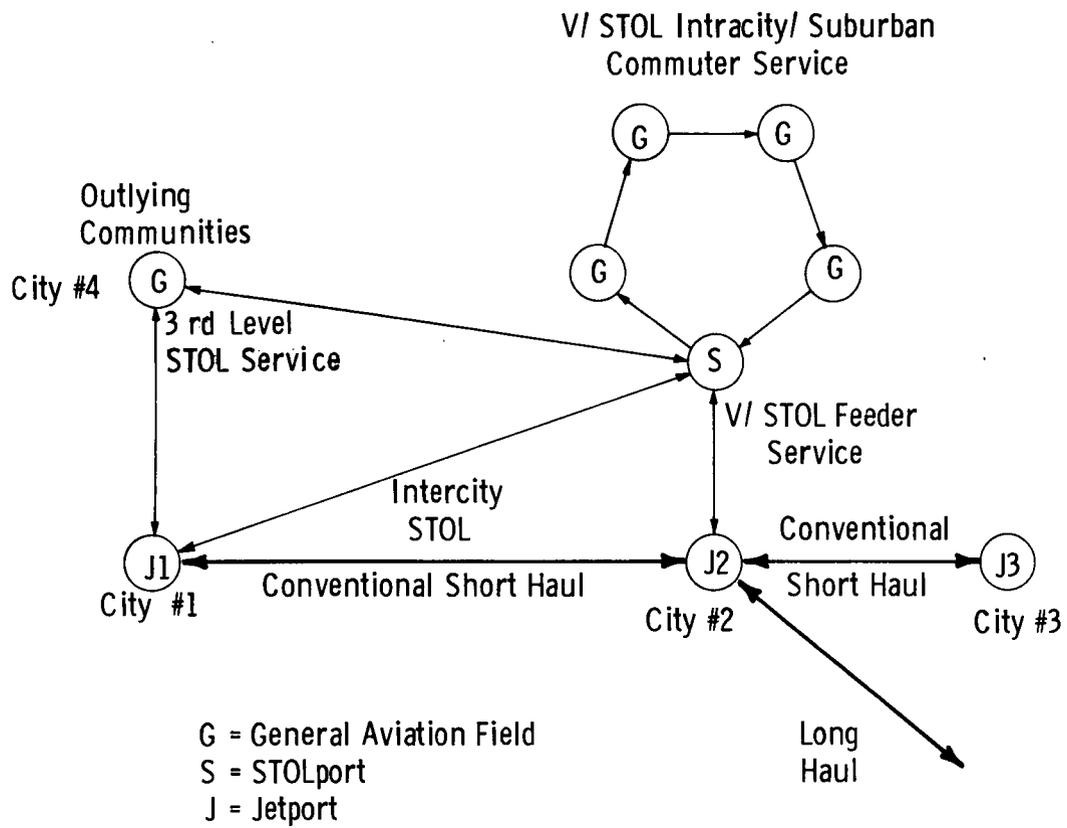


Figure 3.5-7 STOLport/ Jetport Services

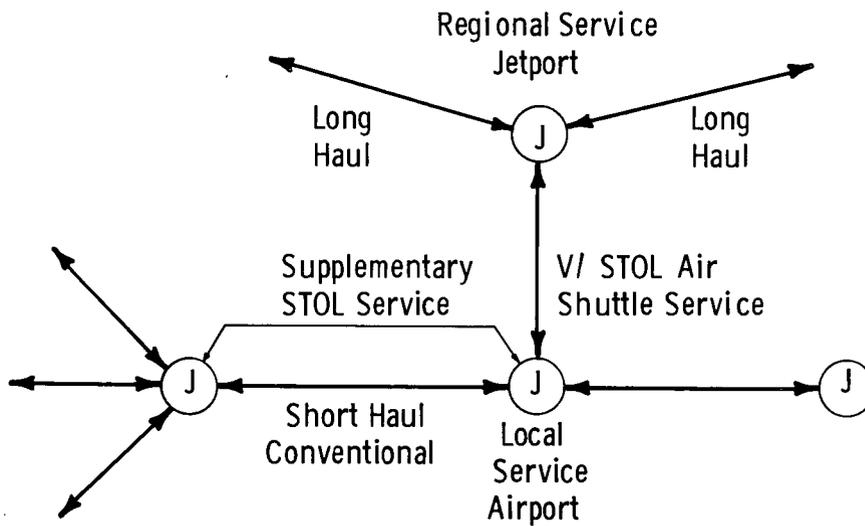


Figure 3.5-8 Jetport/ Jetport Services

Case 1: STOL/CTOL Operations on the Same Runway

There are several possibilities here. For example, STOL aircraft might land along with CTOL aircraft at CTOL speeds. This is sometimes done in the case of Twin Otter operations at jetports today. STOL characteristics would not be necessary at the jetport, but might be needed at the other end of the line. In this case the addition of STOL operations would not impose any unusual burden on the ATC system, but it would certainly not do anything to alleviate congestion.

There are also various ways of conducting single-runway landing operations in which the STOL vehicles would use a STOL landing configuration. STOL and CTOL arrivals might share a common final-approach path (with increased separation to allow for the disparity in approach speeds); the transition to STOL speeds could be delayed as long as possible; or the STOL vehicles could be sequenced into the CTOL arrival pattern near the runway threshold. Such procedures would probably have a deleterious effect on runway capacity as indicated in Section 3.5.1, and would be less desirable for that reason. Delayed transitions and close-in maneuvering would also add to pilot and controller workload.

Thus, it does not appear that conducting STOL and CTOL operations on the same runway is advantageous from an airport capacity point of view; in fact, it may be markedly disadvantageous given present separation requirements.

Case 2: STOL/CTOL Operations on Parallel Runways

The separation between the parallel runways determines whether simultaneous (completely independent) landing operations are permitted under VFR or IFR conditions.* Under VFR conditions the FAA will permit such operations if the separation between runways is at least 700 feet. Under IFR conditions and with radar surveillance, simultaneous ILS approaches to parallel runways are permitted if the runways are at least 5,000 feet apart. The Air Traffic Control Advisory Committee has suggested that the runway separation requirement might safely be reduced to 2,500 feet in the course of upgrading the Third Generation System. The microwave landing system (MLS) currently under development would be a key factor in such a decision.

Because STOL runways have relatively modest land requirements, it might be possible to locate several STOL strips around the perimeter of the airport which would provide the required separation from any CTOL runway

* Paragraphs 523, 1362, and 1363, Terminal Air Traffic Control.⁶

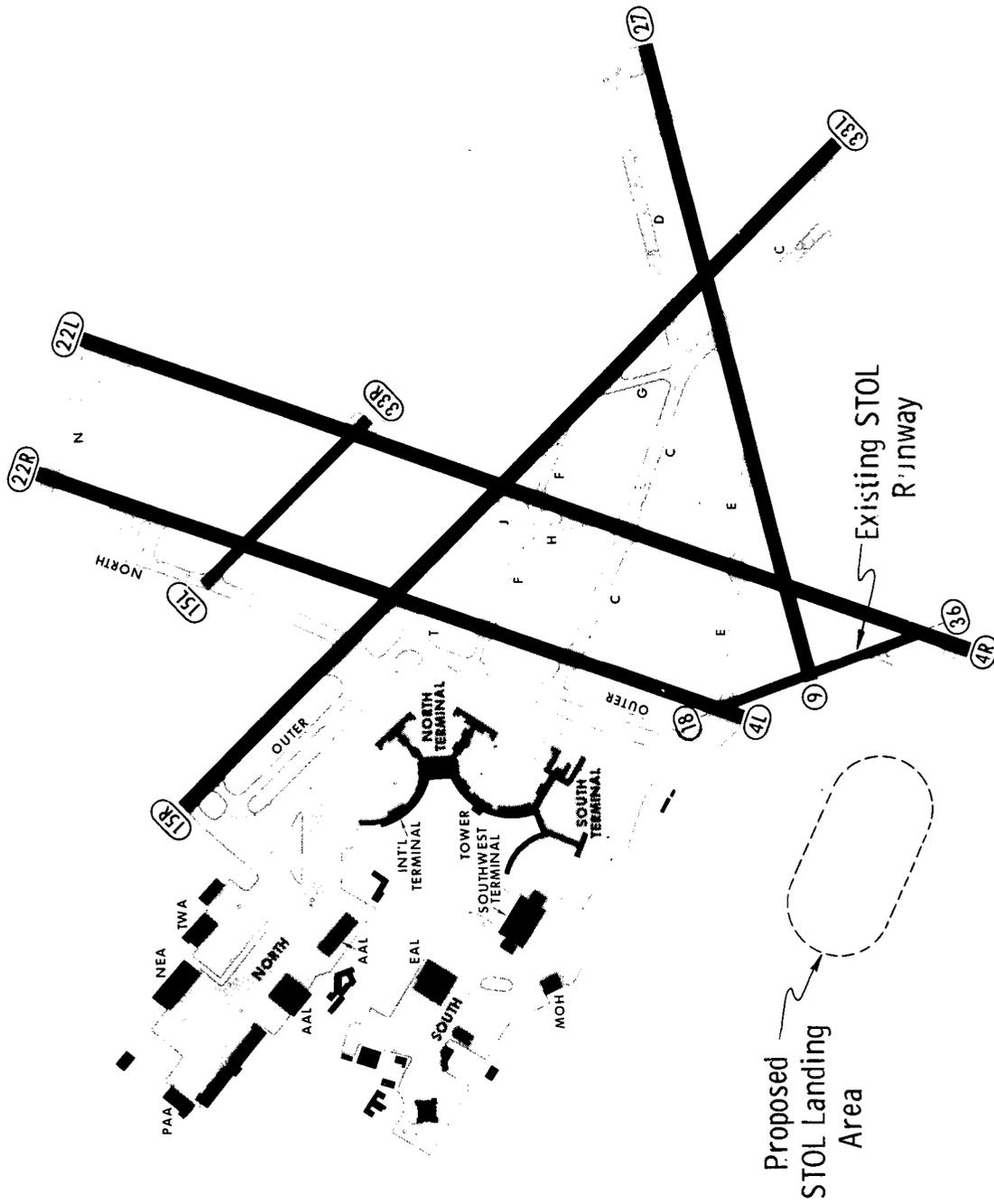


Figure 3.5-9 STOL Runways at Logan International Airport

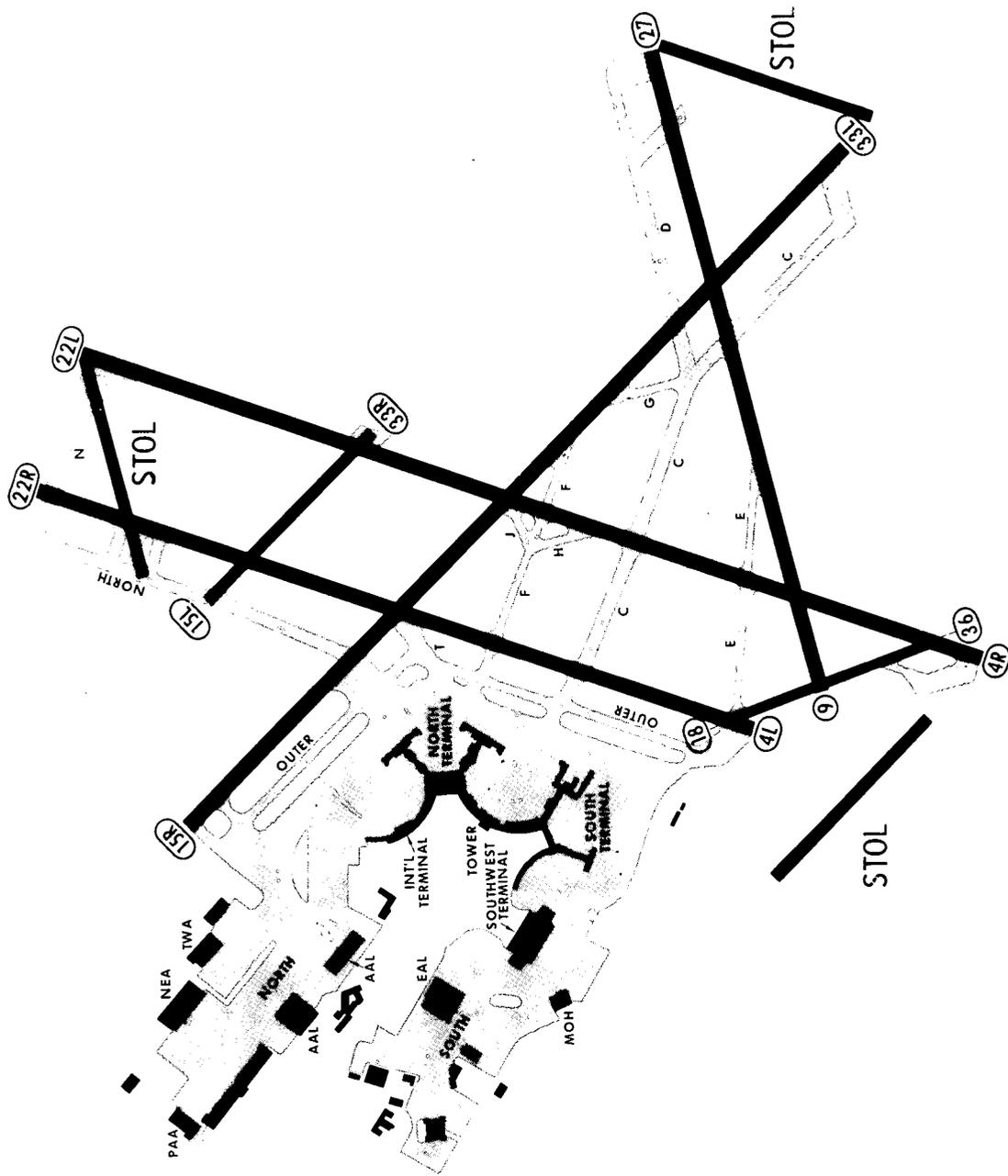


Figure 3.5-10 Possible Locations for Independent STOL Runways

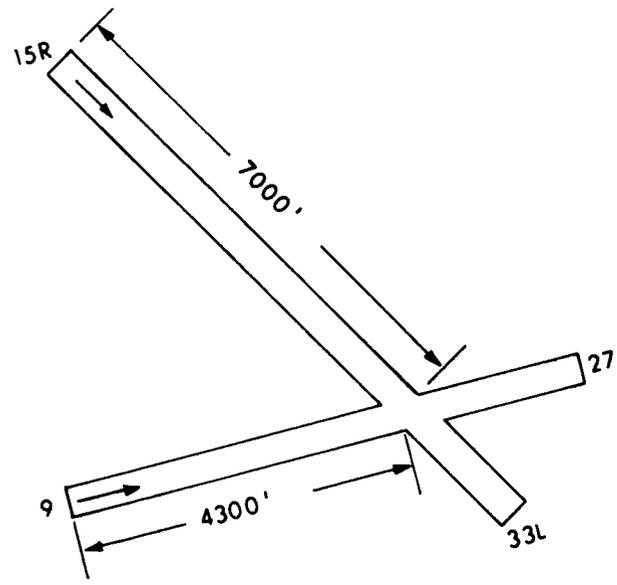
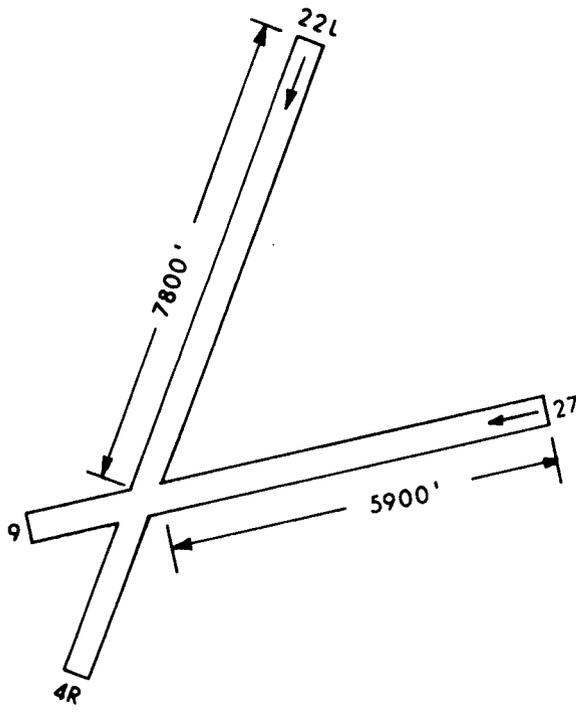


Figure 3.5-11 Runway Chart for Simultaneous Landings on Intersecting Runways at Logan International Airport (Not to Scale)

in use. One example of STOL runway placement to allow simultaneous ILS approaches is illustrated in Fig. 3.5-10 for Logan Airport (runway 9/27 does not currently have an ILS). Unfortunately, the remote runway locations shown in Fig. 3.5-10 would lead to increased taxiing time for the STOL vehicles and might cause runway/taxiway conflicts. These ground delays might be acceptable if the STOL vehicles could avoid the large inflight delays (≈30 min) sometimes encountered by CTOL operations at the busiest airports.

Case 3: STOL/CTOL Operations on Intersecting Runways

Simultaneous landings under VFR conditions are permitted on intersecting runways provided that the smaller or lesser performance aircraft using the secondary runway are capable of stopping before reaching the intersection.* Using Boston's Logan International as an example, simultaneous landings are authorized for runway combinations 22L/27 and 15R/9 (see Fig. 3.5-11). The use of intersecting-runway 9/27 is restricted to aircraft of 12,500 pounds or less maximum landing weight, and DC-3 type aircraft. No restrictions apply to aircraft landing on the other runway.

Simultaneous operations of the type described are not currently permitted under IFR conditions. Missed approaches are potentially dangerous in this case and it may be that visual monitoring of the situation from the tower is essential to ensure safety. Simultaneous missed approaches might require sudden evasion maneuvers. Such operations are also prohibited when braking action on the runways is less than good.

Although simultaneous operations on intersecting runways are not permitted under IFR conditions, time-synchronized operations are.** In this case, the controller must synchronize operations such that the first arrival has either left the runway, stopped short of the intersection, or passed through the intersection before the arrival on the intersecting runway has crossed the landing threshold. The synchronization thus eliminates the possibility of a conflict at the intersection.

This type of approach procedure is of limited usefulness at the present time for the following reasons:

1. It is difficult for the controller to implement such synchronization procedures efficiently without additional aids. The computer-aided metering and spacing system based on ARTS III hardware (see Section 2.3) should be able to provide this assistance in the future.

* Paragraph 561b, Terminal Air Traffic Control.⁶

** Paragraph 516a, Terminal Air Traffic Control.⁶

2. The pilots of conventional aircraft are reluctant to land on crosswind runways under IFR conditions, particularly since these runways tend to be shorter and non-instrumented. STOL vehicles would be better suited for this type of operation.
3. The 3-n.mi. radar separation currently required between arrivals on separate runways acts to limit the possible airport capacity increase such operations might provide. In most instances, in-trail separation would have to be increased in both arrival streams in order to provide the required inter-stream separation. If both runways were ILS- or MLS-equipped and radar monitoring were available, then perhaps the 3-n.mi. separation rule could be waived for synchronized approaches to intersecting runways as it is for simultaneous approaches to parallel runways.

This latter type of operation (with the inter-runway 3-n.mi. separation rule waived) is particularly attractive for the STOL/CTOL case. Given sufficient crosswind capability, the STOL vehicle could land on intersecting runways or taxiways that could not otherwise be used; the operations could be conducted VFR or IFR in a substantially noninterfering fashion; finally, since the operation is synchronized, the STOL vehicle might be able to expedite the taxiing process by leaving the runway either before or after the intersection depending on the location of the terminal building.

To summarize the above cases, noninterfering, capacity-enhancing STOL/CTOL operations at jetports should be possible if the STOL and CTOL vehicles use separate runways. Under IFR conditions, the two possibilities for noninterfering landing operations would appear to be (1) simultaneous ILS (or MLS) approaches to parallel runways, and (2) synchronized operations on intersecting runways. In the first instance, parallel STOL runways having sufficient separation from the CTOL runways would be needed. In the second instance, additional aids to the controller (such as the ARTS III metering and spacing system) would be necessary to increase efficiency and reduce controller workload, and the 3-n.mi. separation rule would have to be amended. In examining the tradeoffs between these two types of operations, particular attention must be paid to taxiing delays caused by remote runway locations and taxiway/runway interference.

Confirmation of the above conclusions in Cases 1 and 2 is provided by the results of an FAA study of VTOL and STOL operations in the terminal area which used the simulation facility of the National Aviation Facilities Experimental Center (NAFEC).¹² Several approach conditions and separation criteria were investigated using the Los Angeles terminal area as a simulation test bed. It was found that the

V/STOL vehicles could be accommodated using current operating procedures, but that "computer assistance in scheduling aircraft into the terminal area and establishing proper spacing of the V/STOL aircraft on final approach would have resulted in a more efficient operation."

Only Cases 1 and 2 of the above classification were studied in the NAFEC simulation inasmuch as synchronization aids are still in the development stage and were not available. The results were as might be expected. With respect to V/STOL and CTOL landings on the same runway it was found that "when V/STOL aircraft operated at speeds comparable to those of conventional aircraft..., smooth and efficient traffic flows resulted." However, "when V/STOL aircraft operated at final-approach speeds common to type, and were mixed with conventional aircraft in the same final-approach airspace, delay was encountered by conventional aircraft and an inefficient use of airspace resulted." When the V/STOL and CTOL aircraft operated on separate and independent parallel runways, an orderly flow of traffic resulted once again.

3.5.2.4 Implementation Requirements

Let us now examine some possible system requirements for implementing these procedures. Two principal objectives should be pursued: (1) independent parallel-runway operations, especially with reduced runway separation, and (2) synchronized operations on intersecting runways. Although these are not strictly STOL/CTOL procedures, the high maneuverability of the STOL vehicle should be taken into account in setting safety standards.

With respect to the first objective, it would appear that there is a need for a more accurate and versatile instrument landing system to reduce the dispersion of aircraft on final approach. It is anticipated that the microwave landing system now under development would serve this purpose. In addition, the aircraft must be equipped with a control system which will enable it to acquire the runway centerline or fly curved approaches accurately and safely.

With respect to the second objective, specialized displays may be required to assist controllers in maintaining the phasing between CTOL and STOL operations. Special software modifications to ARTS III metering and spacing control algorithms may be appropriate when one of the runways is dedicated to STOL operations. For example, the large difference between final-approach speed and cruise speed available with a STOL vehicle should make the timing of the transition to STOL configuration an effective synchronization tool. In general, one would expect that feeder fixes for STOL arrivals could be located closer to the runway than for CTOL arrivals and that airspace could be conserved by making sequencing areas smaller.

Synchronization of operations might be useful for the reduced-separation parallel-runway case as well, in order to avoid arrival/departure (or wake turbulence) interference. As an example, assume that the conventional aircraft lands first and that the STOL vehicle lands 40 sec later on the STOL strip shown in Fig. 3.5-12. As soon as the STOL vehicle has safely touched down, the CTOL arrival will have completed its rollout and will be exiting the runway, at which point a departure can be released on the CTOL runway, and so forth.

The simultaneous or synchronized operations proposed here would require continuous monitoring of the aircraft all the way to touchdown. Any violation of the assigned airspace would necessitate the execution of a missed approach on the part of the STOL aircraft, regardless of which aircraft was responsible for the violation. The STOL vehicle, being more maneuverable, must accept the burden of missed approaches, blunders, and other emergencies encountered in this operation. To achieve the accuracy and speed required in monitoring this operation, a special short-range surveillance radar with fast sweep may be required. This might be coupled with automatic collision avoidance commands generated by advanced ARTS III or IPC systems to provide the fast reaction time required in this situation.

It should be emphasized that the IFR multiple-runway procedures and equipments suggested here should not be construed as necessary conditions for the introduction of STOL at metropolitan jetports. Low-density STOL operations can and do use single-runway procedures with minimal impact upon airport operations. Similarly, a VFR-only type of STOL service should be easy to implement in most cases.

3.5.2.5 Recommendations for Further Study

If STOL aircraft are to operate from congested airports, they must operate compatibly with conventional aircraft. The key issue in such mixed operations is capacity versus safety. If capacity is to be increased with the introduction of STOL, then the consequent increase in congestion must be offset by an increase in safety. This applies not only to landing aircraft but to departures and to aircraft in the terminal and en route phases of flight as well. Simultaneous or synchronized operations should be possible, but a detailed analysis is needed to define the requirements for these types of mixed operations. A safety analysis is needed to determine separation criteria for CTOL and STOL aircraft. If STOL/CTOL runway separation is to be reduced then one must examine possible improvements in ground surveillance, monitoring, and navigation systems, as well as improvements in aircraft instrumentation. Some improvements will be needed in the ATC system and compatible abort procedures must be defined in order to cope with system failures and blunders on the part of man and machine.

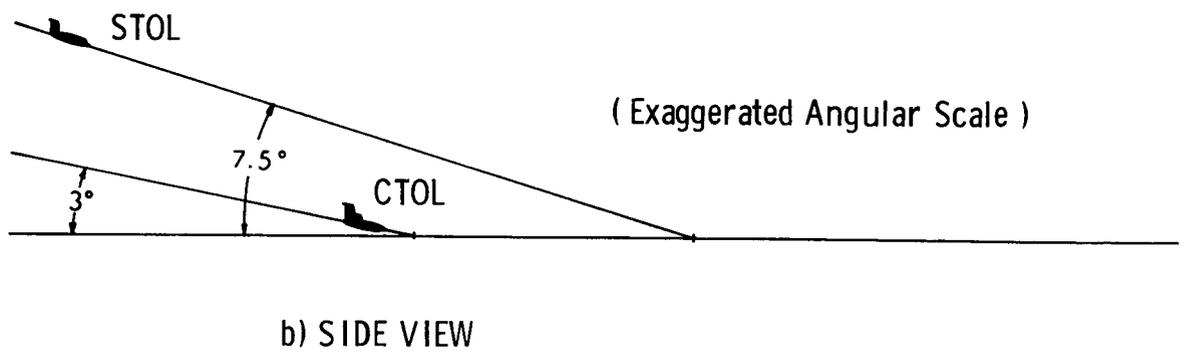
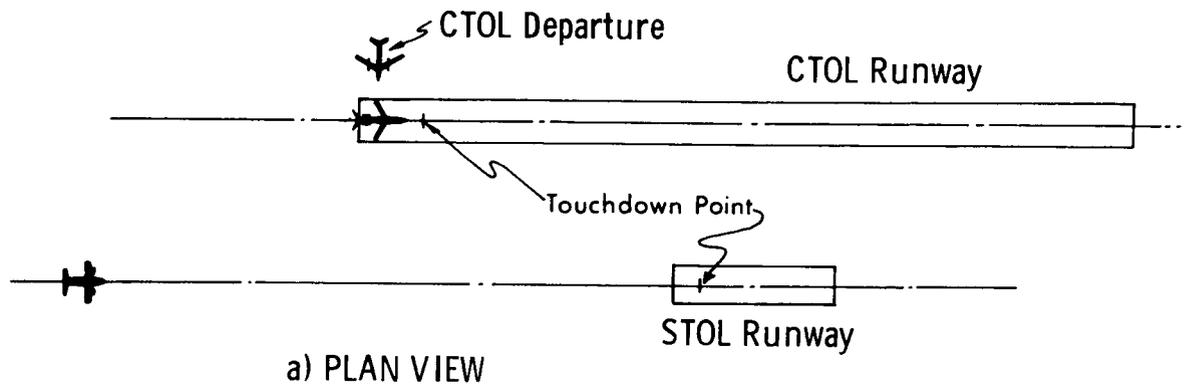


Figure 3.5-12 Synchronized Parallel Runway Operations

The first step in such an analysis is to define an efficient system which, assuming everything works properly, will meet the system objectives with a high degree of reliability. The efficiency of the system can be predicted from a system error analysis (assuming Gaussian error distributions, for example).¹³ One could distinguish between operations under instrument or visual conditions, but for service reliability the system should be designed for CAT II capability.

Although a system error analysis can be used to predict system efficiency, determining system safety is another matter. System safety is strongly influenced by the "tails" of the error distributions and cannot be predicted from a Gaussian error analysis.¹³ The tails are shaped by the failures, blunders, and unlikely events which can affect the system. If the failures and blunders can be detected and corrected, they need not pose a problem. It is the undetected (and hence uncorrected) system failures, both ground and airborne, man and machine, which ultimately determine the safety of any operation. For this reason the system should be designed to detect and cope with as many malfunctions as possible. A surveillance and monitoring system operating independently from the primary guidance, navigation, and control systems must be provided to detect blunders with adequate lead time to cope with potentially dangerous situations. Moreover, the procedures to deal with these situations must themselves be safe and effective and executed in timely fashion. A safety analysis should identify the most likely modes of failure and define equipment, rules, and procedures to deal with them. In general a precise calculation of system safety is not possible; consequently, the analysis should be based not only on mathematical reasoning but on sound engineering judgement as well. Furthermore, a general consensus among the operators, the regulatory agencies, and the system designers must be reached before this type of service can be implemented.

3.5.3 STOLport and Suburban Airport Operations

In this final section, the geographic region of interest is expanded beyond the immediate environs of the jetport to encompass the approach and departure airspace as well as possible non-jetport STOL terminals in the metropolitan area. An examination of the proposed STOL terminal sites in Section 2.2 or Appendix A reveals that the use of both downtown STOLport facilities and suburban general-aviation airfields is contemplated.

Operational procedures for handling V/STOL aircraft in a congested terminal area environment (Los Angeles) were investigated in the NAFEC simulation study mentioned in the previous section.¹² The results of this simulation study and of a later FAA staff study on operations at downtown STOLports¹⁴ are discussed briefly in this section. A second FAA simulation study of STOL operations in the New

York City area is currently in progress and should add much useful data on STOL procedures.

It should be emphasized that the extent to which STOL operations in the terminal region are problematic depends on the traffic levels contemplated. When large numbers of STOL operations must be accommodated (or when STOL operations are conducted at heavily-used general-aviation airports or jetports), efficient, noninterfering operating procedures become a major consideration.

Several problematic areas were identified in the NAFEC simulation. With respect to the approach airspace, the most pertinent test results were these:

1. Establishing proper separation between the V/STOL aircraft prior to transition proved to be a high-workload task. V/STOL aircraft which decelerate to 60 knots or even less before landing must be spaced farther apart prior to transition than CTOL aircraft for a given final-approach separation. A 15-mile pre-transition spacing was used in the simulation. The task is made more complicated if a range of final-approach speeds or deceleration capabilities are involved. This problem must be solved if closer final-approach separation is to be achieved. To quote one of the conclusions of the study: "The use of the reduced separation standard (2 n.mi.) between V/STOL aircraft on the final-approach course proved of limited advantage because of the difficulty in establishing the desired longitudinal separation at the point of conversion."
2. Because of the workload involved in providing separation for the V/STOL aircraft, an additional controller was required to handle arrivals to the City Center Metroport (the V/STOL facility).
3. Separate arrival routes for V/STOL aircraft were found desirable when the V/STOL and CTOL aircraft landed on independent runways, but were of no value when they landed on the same runway. Because of airspace limitations, it was not possible to provide separate routings for V/STOL arrivals from the NW.

With respect to departures, the high V/STOL climb rate gave controllers greater flexibility and allowed them to expedite the flow of traffic.

In 1969, an FAA staff study was prepared entitled: "The Feasibility of Establishing Downtown STOLports in New York City, Los Angeles, and Chicago".¹⁴ The study concluded that downtown STOLports would be feasible from an air traffic control point of view in each of the three cities, but suggested that a network of suburban STOLports might better serve the transportation needs of the Los Angeles area. Since the study did not involve simulation of traffic control procedures, the feasibility conclusion should be regarded as preliminary.

Route structures were suggested that would allow independent STOL operations at a Manhattan STOLport, although the routes suggested have not been integrated with the "metroplex" plan. Such integrated routes will almost certainly involve crossing over and under CTOL traffic using the neighboring airports. The study indicated that further analysis of the adequacy of radio and radar coverage at lower altitudes along the Hudson River would be necessary. Three additional radar controllers would be needed at the New York TRACON, and a crew of seven would staff a mobile tower at the STOLport.

In the Los Angeles area, one of the suggested terminals for STOL operations is Hawthorne Municipal Airport (HHR) located two miles SE of Los Angeles International Airport (LAX). Runway 25 at HHR is proposed as a STOL ILS runway. Simultaneous ILS approaches are conducted on runways 24 and 25L at LAX; since the runway thresholds of runway 25L at LAX and 25 at HHR are offset by approximately three miles, it might be feasible to conduct triple simultaneous ILS approaches to this set of runways. The study indicated that three additional controllers at the Los Angeles TRACON as well as a radar console and communications equipment would be needed to implement this type of operation.

With respect to the Chicago area, the study concluded that Meigs Field would be a feasible STOL terminal from an ATC point of view, provided that an instrument approach procedure (hopefully an MLS) is made available.

Both the NAFEC simulation results and the FAA staff study discussed above indicate that for a STOL system to be viable and relieve congestion, STOL and CTOL operations in the terminal area must be relatively noninterfering. The new "keep 'em high" policy being implemented at major hubs (see Section 2.3) may be helpful in this regard, at least under IFR conditions. By keeping below the CTOL traffic, STOL aircraft would be able to operate out of small airports in the vicinity of a large jetport (such as Norwood, Hanscom Field, South Weymouth, and Beverly in the Logan International Terminal Area at Boston).

Under VFR conditions, compatibility with general aviation will have to be a major consideration. STOL aircraft will have to share urban airspace and airfields with the general-aviation fleet. Although general aviation would probably be directed around restricted areas and flight paths by means of intermittent positive control, airborne collision avoidance hardware may be desirable to ensure the safety of commercial STOL operations. The form of the collision avoidance system is as yet undetermined. A promising development that may combine the collision avoidance and navigation functions is the Traffic Situation Display (TSD) currently under development at M.I.T. by a consortium of three laboratories: the Electronic Systems Laboratory, the Flight Transportation Laboratory, and the Man-Vehicle Laboratory.

By displaying in the cockpit a portion of the information that is provided to the ground controller by ARTS, the TSD will enable the pilot to monitor his proximity to neighboring traffic more effectively.

In conclusion, the cited studies indicate that STOL operations at separate STOLports and suburban airports within major terminal areas can be accommodated using existing procedures for the most part. One or more satellite positions at the TRACON may be necessary as well as tower controllers for special STOLport facilities. Avionics and ground-system improvements should concentrate on the following problem areas:

1. Assistance to the controller in establishing pre-transition separation.
2. Methods for standardizing STOL deceleration profiles during transition.
3. Methods for reducing the airspace required for controlling STOL/STOL separation on final approach.
4. Ways to improve the adequacy of navigation aid and radar coverage at certain problematic STOLport sites.
5. Methods for enhancing the safety of STOL operations at suburban airports.
6. Collision avoidance assistance for STOL pilots operating amidst general-aviation traffic in the terminal area.

It is recommended that limited-scale demonstration projects be undertaken using actual STOL vehicles to assist in identifying operational problems and in establishing detailed operating procedures.

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APPENDIX A

STOLPORT SITE SELECTION

A.1 INTRODUCTION

A need exists for an alternative or supplementary short-haul transportation system in the Northeast Corridor. This consensus has been the net conclusion of a vast number of studies concerned with the transportation problem in the complex of cities along the U.S. Atlantic seaboard between Maine and Virginia. The most awesome study, at least in terms of dollars (about \$12 million), was the Northeast Corridor Transportation Project, which was completed in 1970. It focused on the expected transportation needs of the BOSWASH megalopolis after 1975, and identified various systems, or combinations of systems, which would satisfy those needs (see Exhibit 1).

The study indicated that STOL aircraft were available without need for much technical innovation. Indeed, both Eastern Airlines (in the fall of 1968) and American Airlines (in the spring of 1969) undertook STOL demonstration/evaluation flights with the McDonnell-Douglas 188 (Breguet 941), an aircraft assumed to have the characteristics and payload potential of an airline transport. Both programs concluded that STOL was feasible, and would accomplish the objectives of:

1. reducing congestion and excessive burdens on air traffic and airport systems;
2. utilizing unused airspace and airport areas;
3. providing better service to the traveling public at reduced cost to the airlines.¹

Proponents of an improved highway network could argue that better interstate routes would also accomplish the above objectives. Indeed, the reason most often advanced for the slow growth of air taxis and commuter airlines has been the excellence of highways to serve the traveling public and the consequent growth of the car rental business. However, there is no denying the need for some relief of

air congestion and some method of shortening access time to the terminal, if air is the preferred mode of travel. For Northeast Corridor traffic it has been estimated that from 50% to 70% of total travel time is spent accessing and egressing from the system. The STOL system has the potential of reducing this access time.

The complete STOL system can be defined as consisting of the STOL vehicle and the onboard avionics, properly located STOLports, an air traffic control system to expeditiously and safely handle the vehicles and any interfaces they would have with CTOL, any required new ground transportation links, and finally, a set of regulations and procedures that would allow STOL to operate in the megalopolitan environment without massive community protest.

Of the elements comprising the system, STOLports appear to require the largest initial economic commitment, if built new and located near the city center. Ideally they should meet a wide variety of local travel patterns:

1. Primary access to large commercial centers from other centers within a radius of 500 miles.
2. Primary connecting traffic at major hubs for transcontinental and international flights from communities within a radius of 500 miles.
3. Second-level interconnecting and suburban traffic to and from communities within 500 miles.
4. Traffic between small-city pairs and to hubs and larger cities.²

However, there is a problem, which has been felicitously described by the CAB:

"Civil authorities are reluctant to commit high-priced land areas and expensive construction costs for a transportation system that does not exist and for which the outcome is in doubt. Airlines will not order aircraft for which suitable areas and facilities for operation are not available. Without firm orders, aircraft and engine manufacturers are hesitant to allocate money and time to large-scale development of vehicles for which there may not be a market.

Thus, it appears that development of STOL and VTOL ports, and the entire new concept of air transportation are dependent on political and economic considerations rather than technology."³

The major political consideration is STOLport location. The field of operations management has developed many techniques to select an optimum site, given sources, destinations, and expected demand; yet one of the variables that can make all the other ones irrelevant is "community acceptance."

A.2 EVOLUTION OF SITE SELECTION

The STOL concept is not new; it is new only in the sense that it is now being viewed as a whole transportation system. As a matter of fact, all aircraft built before World War II can technically qualify as STOL aircraft. A DC-3 can take off with a moderate load on less than 1,000 feet of runway.⁴ In the late 1940's STOL aircraft were viewed quite favorably by the populace over which they flew, as were the first STOLports.

"...ten strips were actually installed in the metropolitan Boston area and used experimentally for a year with a number of light aircraft that were progressively quieted until no further neighborhood objections were raised. No undue aircraft weight, cost or performance penalties were encountered. The results were so eminently successful that the Massachusetts legislature passed a special bill making the public park properties that had been used for the tests permanently available for continuation of such air services, assuming, of course, that aircraft manufacturers would soon supply STOL aircraft with quieted propulsion along the lines the test program had already demonstrated to be feasible."⁵

Presumably the General Court of Massachusetts did not envision the STOLport described by de Havilland in 1969:

"Separation standards appropriate to STOL aircraft would permit typical hourly capacities for a single runway of 50 operations per hour or 150,000 operations per year. Using a 48-seat aircraft (DHC-7) with an 0.6 load factor, 4.3 million people would pass through the STOL port in a year."⁶

Somewhat more appropriate STOLstrips have been developed since the late 1940's, but they have one thing in common with the public parks of Massachusetts: they have only been used for demonstrations. These strips have been built at various Northeast Corridor airports (LaGuardia, Washington National, Logan International), and were used by Eastern Airlines in their STOL demonstration program in 1969. These strips have been located on airport areas where, (1) land was not being utilized, and (2) they would cause a minimal amount of interference with CTOL traffic. No particular attention was paid to passenger convenience.

At the same time the STOLstrips were being installed, various studies of STOL and V/STOL systems were under way. The studies considered below are by no means all-inclusive, but they do present the type of criteria that have governed STOLport location. They are, chronologically:

1. M.I.T. Flight Transportation Laboratory Systems Study (MIT/FTL Report TR 65-1, 1965);

2. McDonnell V/STOL Study (FAA-ADS-74, Volumes I-III, 1966);
3. De Havilland STOL Study (CAB Exhibits deH-13 to deH-18, 1969);
4. MITRE V/STOL Study (MTR-1653, 1971);
5. M.I.T. Thesis (Swan, 1971).

The MIT/FTL study addressed itself to the 1980 time period, and, specifically, to the Northeast Corridor. The terminal location rationale is presented as follows:

"For the initial study fifty terminal sites were chosen. An attempt was made to locate these sites at existing airports very near the downtown portion of the smaller cities and at airports plus actual downtown locations at the larger metropolitan areas. This was done so that existing airport facilities could be utilized; connecting links could be made with flights outside the corridor; noise in heavily populated areas could be kept to a minimum; and the terminal costs could be kept as low as possible.

"The Department of Commerce suggested 26 metropolitan areas to be served. These were taken and other cities added on the basis of population size and density."⁷

The study recognized that downtown (Central Business District - CBD) locations might generate special problems and expanded:

"As the siting problems will depend on local political factors, it is impossible to select appropriate downtown sites at the present time. In general, it will not be possible, nor desirable to select the highest value land in the city center. Instead, waterfront sites, railroad yards, elevated structures over freeways and cloverleaves, etc., will probably be used, and such sites seem to be readily available in all these cities. The cost of land acquisition of such sites is still quite high, and seems quite variable from city to city. Noise considerations, obstacle-free approach paths, over-water approach paths, zoning regulations, connection to other transportation facilities, etc., will all be factors in determining exact locations for V/STOL terminals."⁸

The McDonnell study addressed itself to roughly the same time period, and considered the entire United States. The study assumes that downtown (CBD) locations must be made available at all major cities for V/STOL ports. The argument is made that V/STOL ports near the CBD are (almost) mandatory for the city to survive as a viable social and economic unit.

"Siting must certainly be adjacent to the central business district to realize full traffic potential and for the central business district to benefit, yet land costs are high, it is difficult to assemble land parcels into large packages without urban renewal assistance, and of course, noise levels become problematic the closer such terminal is to the core. However,

in many large cities there is frequently a sector in which land value gradients drop sharply a short distance from the core. This is frequently the beginning of the "grey belt" and in many cities is adjacent to a waterfront. The opportunity of combining a STOL/VTOL terminal with urban waterfront renewal should not be overlooked . . .

Aside from urban waterfront renewal, other grey areas adjacent to the central business district core or frame similarly represent unutilized potentials. The value of considering a STOL/VTOL port for such locations is that the terminal's productivity would be increased; the underutilized resource of air traveler time and the underutilized resource represented by grey area land would both be put to work . . .

A central STOL/VTOL port could bring a new dynamic image to the central city and become a key element in a coherent and rational transportation system. Operated as a system with the present airport used for long-haul flights, the STOL/VTOL port could become a transportation terminal or the center for communications-based industry, in contact with all parts of the central business district by minibus and closed channel TV. The STOL/VTOL terminal could thus become a form-creating force . . .

In the long-run the central city's role will probably increase in importance as a result of market forces, as the U.S. moves further into a service-oriented, post-industrial economy. Transporting goods involves shipping costs plus pipeline inventory costs, but moving people involves the value of time lost in transport.

It seems probable that in the transition of our urban regions to some new, more complex structure, the central cities might add a note of assurance to its future role by taking advantage of this new STOL/VTOL technology. An investment decision of this type would perhaps add confidence that a structural form was beginning to emerge, with the central city reasserting its unique values."⁹

The de Havilland study of terminal locations assumes that:

"The object of a STOL transportation system is to provide frequent service from terminals conveniently located with respect to the traffic generating areas. Therefore, the distribution of local origins and destinations of travelers indicates the preferred locations for STOLports."¹⁰

As to the special problems of the CBD, the de Havilland study observes:

"Generally speaking, the central business district is the highest traffic generating area, and thus a STOLport should be located as close as possible to it. From the preliminary information responses, it would appear that appropriate sites are readily available, even in the built-up areas of the larger cities. Most of the sites presented in this Exhibit are over railway depots or on bodies of water.

To provide easy access to more of the major traffic generating areas in larger cities, more than one STOLport site is required. In many cases, existing airports may be used. Care must be exercised however, lest in the tempting desire to minimize the initial costs and problems of setting up the system, a site is chosen that is less accessible and hence less attractive to the passenger. In Exhibit deH-1, pages 63 and subsequent, it is shown that STOLport costs are a small fraction of the total system costs, and hence it is a good investment to provide sites that are most attractive to the traveller.

This same logic is the reason that downtown STOLports have been proposed for Washington and Boston, even though the major airports are not too far distant. The traffic available in the downtown area more than justifies a convenient site. Congestion at these conventional airports is also a consideration."¹¹

The results of the de Havilland study on terminal location are presented in Exhibit 2. These sites are proposed for the time period of 1978.

The more recent MITRE study recognizes that:

"The attractiveness of short or vertical takeoff comes primarily from the increased probability of being able to find a suitable site with good access. The key factor is the flexibility of relatively small, community-acceptable STOLports or VTOLports."¹²

The study proceeds to estimate demand and then develops site locations. The results are presented in Exhibit 3.

"The STOLport sites used are the result of consultation with the FAA for general location and have been given what appear to be reasonable map locations for the purpose of estimating access time and cost. The sites were not evaluated in detail and should not be construed as specific recommendations for airport locations but only as representative possibilities."¹³

Only after the site selection, for the purposes of the study, has taken place, does the caveat appear:

"The location of terminals is partly a local political decision. Air terminals have encountered increasing community resistance due to environmental pollution. Terminals located close to densely populated areas are likely to meet the most community resistance. The more terminals proposed, the higher the probability that one or more will meet insurmountable community resistance. Thus, strategies for reducing access time must consider the possibility of community resistance."¹⁴

"Lowering access times by relocating terminals closer to population centers or by increasing the number of terminals is the most effective means of increasing demand. However, the serious problem of community acceptance must be kept in mind in any decision affecting terminal location."¹⁵

The yet more recent M.I.T. Thesis¹⁶ is noteworthy, as it is the first study that does not postulate a downtown Manhattan STOLport, nor one in the CBD of Boston. One can conclude that greater awareness of community acceptance problems, combined with staunch opposition in New York to an actual STOLport, has had an effect. The sites are listed in Exhibit 4.

Additional criteria that must be considered when a STOLport site approaches reality are:

1. Both VFR and IFR traffic procedures.
2. Relationship to other airports and airspace utilization, current and proposed.
3. Aircraft operational performance.
4. Compatibility of the STOLport with surrounding land uses, particularly with respect to noise.
5. Effect of existing and proposed obstacles on aircraft operations.
6. Operational usability of the site related to climatological conditions including crosswinds, temperatures, precipitation, ceiling, and visibility.¹⁷

The above criteria relate to problems in airspace utilization, i.e., air traffic control (ATC) problems. These can be summarized as follows:

- (a) "A potentially dramatic increase in the number and density of terminals in a metropolitan area.
- (b) Substantially more complex airspace in high density terminal areas.
- (c) Materially higher load, especially in terms of numbers of takeoffs and landings within high density metropolitan areas.
- (d) Substantially increased number of routes especially within high density metropolitan terminal areas.
- (e) Materially increased numbers of general aviation aircraft and a mixing of commercial aircraft with general aviation in traditionally general aviation airspace.
- (f) The requirement for V/STOL operation under adverse weather conditions.
- (g) The requirement for noise control in densely populated areas."¹⁸

From the STOL flight demonstrations of Eastern and American Airlines, the conclusion was drawn that largely unused airspace could be utilized when the STOL aircraft were equipped with special navigation systems. However, it is by no means clear what effect STOL fleets would have upon the current or future ATC systems.

A.3 OBSERVATIONS AND CONCLUSIONS

"No area of new technology has been accompanied by so much promise and so little fulfillment as V/STOL civil aviation. Witnesses, government and industry alike, have paraded before Congressional committees for a decade promising that many of the nation's short-haul transportation problems are near being solved, or are solvable, by this V/STOL aviation. But as we enter the 1970's we find distressingly little fulfillment of these promises. What are the reasons for the difficulties and delay?"

So writes Raymond Bisplinghoff, Deputy Director of the National Science Foundation in a guest editorial in the December, 1970, issue of *Astronautics and Aeronautics*. His conclusions are that:

"Like so many similar experiences in the past decade, we have discovered again that the existence of a new technology is not both a necessary and sufficient condition for putting it to work. But it can be argued in this case that there is also a genuine social need. After all, the rapid deterioration of short-haul transportation in urban areas of the East can be perceived by anyone who uses it. Even the coincidence of a new technology and an accompanying social need, however, has not proved enough. Difficulties and delay seem to be due to planning and execution—the skills normally attributed to the entrepreneurs rather than to the scientist and engineer."

There are other answers. From the private sector a spokesman at a presentation to NASA/DOT/USAF in December, 1970, described the industry's point of view:

"There presently is a very real need for a short-haul air transportation system, but because of several factors, there is no market, and it is markets which the private sector traditionally has responded to. Air vehicles like the 747 were developed by the aerospace industry to operate within an existing system of ATC, airports, ground access, and so on.... There is no short-haul STOL system. There are no STOLports. There are no regulations specifically for STOL operation. There are no noise standards for STOL aircraft. There is no ATC system to handle the vehicle's different characteristics. There is no coordinated plan for ground transportation links to interface with very high volume traffic into runways near centers of demand. There is no one Federal agency with responsibility. In other words, we must come to grips with complex issues of intermodality, land acquisition, rule-making, community acceptance—things which the private sector has never integrated successfully. In short, this new system would make Federal involvement necessary."

Almost all answers to the question of why there is not a STOL system now suggest that a systematic approach to the problem is necessary. Suggested solutions include the establishment of a quasi-public corporation, putting all of the federal

STOL activities (NASA, DOT, CAB, USAF) under one roof, and/or proclaiming the new short-haul air-system to be a national goal, somewhat akin to Apollo.

Yet there are indications that the establishment of a STOL system in the United States will not be easy, even if the above solutions are adopted. First, there exists general doubt that systems analysis is an appropriate tool to be used on transportation problems:

"System analysis, which attempts to plan based on deterministic behavior models, violates the credibility of the non-defense customer. The goals and needs of social systems are complex, conflicting, and indefinable. They are, after all, collections of emotions and we do not know how to quantify or compare emotions. And we do not understand the mechanism of individual or crowd behavior—as economic forecasters will reluctantly testify. In sum, we don't understand the "black boxes" which the system engineer so blithely thinks he can either describe or program for definition by someone else...

To model just the demand of transportation in California, for instance, one must collect the significant economic data of not only the state but also of most of the nation and develop as well some coefficients to reflect international trade. In practice one is forced to rough approximations which transform determinism to generalization. And with that goes the credibility of the study to the social planner."¹⁹

Then there is opposition to technology and transportation as a child of technology. Some arguments are reasoned, some not. Senator William Proxmire (D-Wis.) has already announced his intention to oppose STOL development, "Congress must not again become involved with some vague, open-ended, potentially very costly joint undertaking with the aircraft industry."

From the social scientist camp come demands that a transportation system provide amenity. To wit, Lewis Mumford writing in the New York Times (March 15, 1971):

"What is the function of transportation? What place does locomotion occupy in the whole spectrum of human needs? Perhaps the first step in developing an adequate transportation policy would be to clear our minds of technocratic cant. Those who believe that transportation is the chief end of life should be put in orbit at a safe lunar distance from the earth. The prime purpose of passenger transportation is not to increase the amount of physical movement but to increase the possibilities for human association, cooperation, personal intercourse, and choice. A balanced transportation system, accordingly, calls for a balance of resources and facilities and opportunities in every other part of the economy. Neither speed nor mass demand offers a criterion of social efficiency. Hence such limited technocratic proposals as that for high-speed trains between already overcrowded and

overextended urban centers would only add to the present lack of functional balance and purposeful organization viewed in terms of human need . . .".

This is hardly a plea for STOL service between city centers.

Philosophical differences aside, most system studies of STOL can be disputed on the question of validity of the demand model, which forms the basis for most studies. The demand models attempt to quantify the emotions of people expected to use the system, and assign numerical values to the value of time. Yet it can be argued that the value of time changes, depending upon the circumstances.

The total trip time is usually defined as having the elements of actual flight time, access and egress time, processing time, and time to wait for next service (if it is a regularly scheduled service). Some of these constituents of trip time could be considered as "wasted" time, time that cannot be productively used, and so should be assigned a higher cost than others. Thus, processing time could be considered "wasted", while flight time can be used for other purposes, such as reading, working, etc. Similarly, if access is by means of private automobile, then it is more "wasted" than if access is by means of a taxi or some public transportation. Finally, it can be argued that it is not actual trip time that will determine demand for service, but perceived trip time (or any of its constituents). If these times differ appreciably, trip time as assigned by a demand model may be totally irrelevant.

What are the likely developments for a STOL system in the Northeast Corridor? The FAA takes an evolutionary view:

"Creation of an optimum, operational STOL system will not be done in one step. It must be recognized that development will be evolutionary. The interaction among acceptable vehicles, navigational systems, air traffic control procedures and hardware, heliports, STOLports, community acceptance, and other factors requires a step-by-step approach. STOL service may, of necessity, be initiated at an existing general aviation airport. However, the optimum system may require a separate STOLport closer to the city center. Planning for the STOL system should proceed with the goal of evolving to the optimum by reserving necessary airspace and ground areas. This is particularly critical for metropolitan STOLport sites."²⁰

In the private sector, Boeing Aircraft Co. and a consortium of Italian aerospace firms are beginning development of a C/STOL aircraft: that is to say, they are hedging their bets. This planned airplane for 100-150 passengers will have STOL capability, but, if the rest of the STOL system isn't available, Boeing will presumably sell the plane as an advanced airbus.

In Canada, the Canadian government has embarked upon a course to make STOL the most vital part of the Canadian aerospace field. An experimental service will begin in May 1973, between Ottawa and Montreal, using modified (for more comfort, naturally) Twin Otters. What makes this particular demonstration impressive is that construction of STOLports in downtown Ottawa and Montreal has also been authorized, and accepted (at least as of now) by the public.

In the United States, STOLport construction is likely to be far slower. As noted, the FAA expects the system to start at general-aviation terminals. Additionally, STOL strips are likely to be installed at various CTOLports, such as the ones at Logan and Washington National. Massport spokesmen quoted in the Boston Globe (July 4, 1971) are enthusiastic: "We're big boosters of the STOL.... We think Logan would make a perfect STOLport because it is the only airport in the country that's so close to the downtown area of a major city."

This demonstrates in a small way the difficulty with the evolutionary approach. Will STOL be given a fair trial by the traveling public if they fly out of suburban fields or the already crowded CTOLports? To continue with the Boston example, has Massport thought about the likely effect of an additional 4 million passengers upon ground access to Logan? For:

"...congestion of the (business district) core has been greatly increased by the high percentage of vehicle trips which are simply passing through...

A prime example of this is that the access routes to Logan International Airport, a major traffic generator, force most air travelers to pass through downtown Boston on their way to and from the airport."²¹

The largest problem has been with New York City, where many sites have been proposed, yet none implemented except the trial strip at LaGuardia. It is hard to imagine that a STOL system will be developed without a STOLport in Manhattan. Indeed, if there is substance to the argument that perceived travel time is important, is a business traveler likely to journey to Secaucus when LaGuardia appears so much closer?

Of course evolution implies a long time period. One can speculate that if nothing is done to improve the amenities of city living, even the business contingent will gradually leave the CBD, as was argued by McDonnell in its V/STOL study. Thus, as business continues to relocate from Manhattan to White Plains, Armonk and other suburbs of New York City, one can decide that, if this trend continues, there will be no need for a STOLport in Manhattan. Of course, this is somewhat akin to solving the ground transportation problem by totally strangling the flow of traffic to a city.

As to the question, Has STOLport site selection been a contributory problem to STOL system implementation? the answer appears to be: No. STOLport site selection, as practiced in the system studies to date, has remained a paper exercise: only when more specific sites are suggested and attempts are made to implement these suggestions will a more definitive answer be given.

In spite of numerous technical studies, many questions remain concerning STOL transportation systems. Interface of STOL with CTOL at CTOLports appears to be an important problem, along with optimum airspace allocation, airborne avionics, and ground equipment requirements. In the area of STOLport siting, it is recommended that particular attention be paid to the issue of community acceptance in addition to operational usability of the site.

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EXHIBIT 1

ALTERNATIVE TRANSPORTATION SYSTEMS

The Northeast Corridor Transportation Project's cost-benefit analysis of transportation needs along the Atlantic coast between Maine and Virginia showed they could be met in the period 1975-80 by any of nine alternative combinations of systems. The chart below compares the kinds of equipment, the cost and the degree of technological innovation required to assemble each of the nine systems. STOL refers to short takeoff and landing aircraft, VTOL refers to vertical takeoff and landing aircraft, and TACV refers to tracked air cushion vehicles.

System	Modes *	Degree of Technological Innovation	Capital Cost
I	Metroliner TurboTrain	None	70 million
II	Metroliner TurboTrain STOL	None	2.64 billion
III	Rail-150 mph STOL	Some	1.6 billion
IV	Rail-200 mph	Some	2.6 billion
V	TACV-300 mph	Much	3.5 billion
VI	VTOL STOL	Some	1.1 billion
VII	VTOL Rail-150 mph STOL	Some	2.5 billion
VIII	VTOL Rail-200 mph	Some	3.6 billion
IX	VTOL STOL TACV-300 mph	Much	4.5 billion

* Auto, bus and conventional aircraft are included in all nine systems.

Source: CPR National Journal, Vol. 2, No. 19, 9 May 1970, p. 995.

EXHIBIT 2

DE HAVILLAND STOLPORT SITES

City	STOLport	Description	Location
New York	ME	Manhattan East	East River
	MW	Manhattan West	Hudson River
	GI	Governors Island	
	PAS	Passaic, N.J.	10 miles NW of Central Manhattan
	QU	Queens, Long Island, N.Y.	Queens - Nassau area
	WES	Westchester County, N.Y.	18 miles NE of Central Manhattan
Philadelphia	CBD	Central Business District	5 miles NE of Phila. International
	WEST	West Philadelphia	12 miles NW of CBD
	NW	North Philadelphia	17 miles N of CBD
Boston	CBD	Central Business District	2 miles W of Logan Airport
	WEY	South Weymouth	15 miles S of CBD
	HANS	Hanscom Field	16 miles NW of CBD
	BEV	Beverly	18 miles N of CBD
Washington	UNION	Union Station	CBD
	POT	Potomac River Site	4 miles W of UNION
	BETH	Bethesda Area	7 miles NW of UNION
	ALEX	Alexandria Area	9 miles SW of UNION
Baltimore	BAL	Central Business District	10 miles N of Friendship Airport
Hartford	HRT	Brainard Airfield	2 miles SE of CBD
Providence	PROV	Central Business District	8 miles N of T.F. Green Airport
Trenton	TTN	Mercer County Airport	5 miles NW of CBD
Wilmington	WIL	Central Business District	6 miles NE of New Castle County Airport

EXHIBIT 3

MITRE STOLPORT SITES

City	STOLport	Description	Location
Washington	DCA	National Airport	4 miles SW of CBD
	WLDW	Wildwood, Maryland	
	SPRF	Springfield, Virginia	
	LUR	Laurel, Maryland	
Baltimore	BAL	Friendship Airport	10 miles S of CBD
	TOWS	Towson, Maryland	
Ambler	AMBL	Ambler, Pennsylvania	
Levittown	LVTW	Levittown, Pennsylvania	
Chester	CHST	Chester, Pennsylvania	
Albion	ALBN	Albion, New Jersey	
Trenton	TTN	Trenton, New Jersey	CBD
Woodbridge	WDBG	Woodbridge, New Jersey	
Philadelphia	PHL	Philadelphia International Airport	5 miles SW of CBD
	PNE	North Philadelphia	17 miles N of CBD
New York	LGA	LaGuardia Airport	8 miles E of CBD
	PTRS	Patterson, New Jersey	
	SCC	Secaucus, New Jersey	
	MANW	Manhattan West Side	Hudson River
	YONK	Yonkers, New York	
	MTCH	Mitchell, New York	Long Island
ISLP	Islip, New York	Long Island	
Providence	GRN	Green, Rhode Island	8 miles S of CBD
Milford	MLFD	Milford, Connecticut	
Hartford	BRAN	Brainard, Connecticut	2 miles SE of CBD
Agawam	BLAG	Bowles - Agawam, Mass.	
Boston	BOS	Logan Airport	2 miles E of CBD
	BVRU	Beverly, Mass.	18 miles N of CBD
	BED	Hanscom Field	16 miles NW of CBD
	OWD	Norwood, Mass.	16 miles SW of CBD
	HPKN	Hopkinton, Mass.	20 miles W of CBD

EXHIBIT 4

M.I.T. STOLPORT SITES

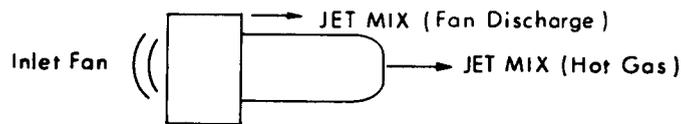
City	STOLport	Description	Location
Washington	WAS	Dulles International Airport	25 miles NW of CBD
	UNION	Over Union Station	CBD
Baltimore	SBL	Over Port Cavington Yard	CBD
Wilmington	SWL	New Castle Airport	6 miles SW of CBD
Trenton	TTN	Mercer County Airport	5 miles NW of CBD
Philadelphia	SPC	Over 30th Street Station	CBD
	SPW	Across Schuylkill R., near Conshohocken	8 miles NW of CBD
New York	SEC	Secaucus, New Jersey	Near LaGuardia Airport
	LGF	Flushing Airport	
	WES	Westchester, Rt. 287 in White Plains	18 miles N of CBD
New Haven	SNH	New Haven Airport	
Hartford	HRT	Brainard Airfield	2 miles SE of CBD
Providence	GRN	Green Airport	8 miles S of CBD
Boston	BOS	Logan Airport	2 miles E of CBD
	HAN	Hanscom Field	16 miles NW of CBD

APPENDIX B

AIRCRAFT NOISE GENERATION

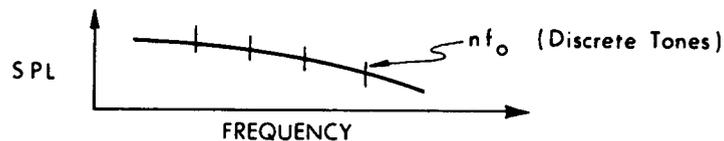
B.1 NOISE SOURCES

The major turbofan noise sources are illustrated below



Jet noise results from the mixing of exhaust gases from the nozzle. It is relatively broadband and highly directive with the angle of maximum radiation at 45 deg to the jet axis. The intensity of the sound is proportional to the eighth power of the jet exhaust velocity. The SAE method¹ is the commonly accepted technique for calculating jet engine exhaust noise. It predicts the sound pressure level at a reference point along the line of maximum radiation.

Fannoise is broadband with discrete tones which have periodic time histories associated with the rotary components of the engine.



At the present time, there are no completely satisfactory methods for predicting compressor/fan noise. For the turbojet engine the broadband noise dominates, but for current fans both broadband and tone noise are important. For future fan jet engines the tones may dominate, depending on such factors as bypass ratios and blade tip speeds.

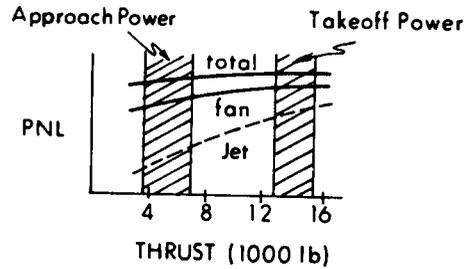
As the bypass ratio and blade tip speeds of current and future fan engines increase, the fan noise becomes the dominant source. This is because more energy

is extracted out of the engine core flow in the turbine to drive the fan, resulting in a lower average exhaust velocity and drastically reduced jet noise. One of the major objectives of NASA's quiet engine program is the reduction of fan noise through nacelle acoustic treatment and engine design.² Although this may successfully reduce the pure tone components, it is felt that this reduction would probably be offset by efforts to increase engine performance through higher bypass and increased blade tip speeds (transonic or even supersonic tip velocities) which result in greater noise power levels generated by the fan.

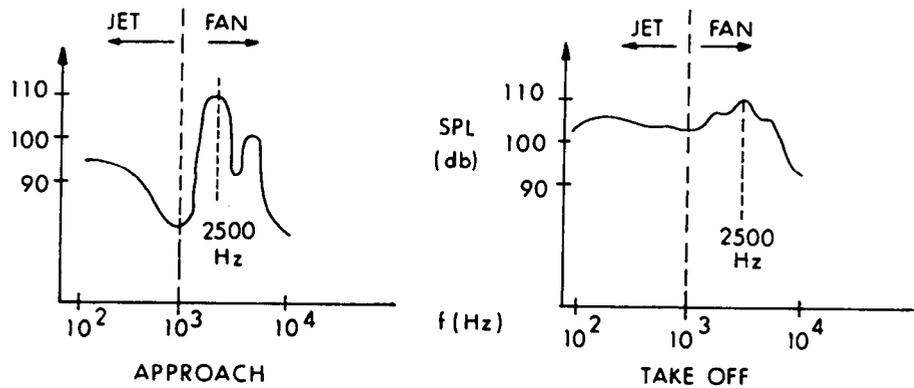
Fan noise is not as highly directional as jet noise. Most investigators are reluctant to give the directivity characteristics because they are usually a function of the fan's operating conditions. However, the data that is available indicates that the angle of maximum radiation is very close to 90 deg with respect to the engine axis.^{2,3}

B.2 EFFECT OF THRUST

The effect of thrust on noise reduction is illustrated below for a typical turbofan engine. Greater noise reductions are realized with the jet-mix source because of the noise dependence on the eighth power of jet velocity.

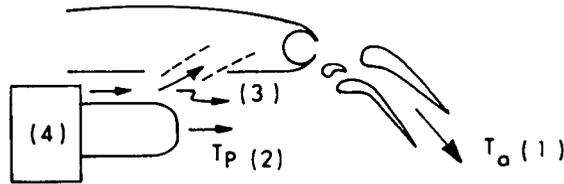


Typical noise spectra for a JT3D engine during takeoff and landing indicate that the fan noise dominates. High-frequency sounds and pure tones are regarded as more annoying than the broadband jet mix.



B.3 A SIMPLE NOISE MODEL

A complete noise model must account for all the noise sources of a particular engine configuration. Consider for instance, the augmentor-wing configuration described in Ref. 4 and shown below.



A control is provided to utilize the fan discharge air for both augmentor thrust and horizontal thrust. The modeling is very complex in that it involves combining noise contributions from all the sources, each with its own directivity characteristics. Additionally, if the primary jet nozzle is rotatable then the directivity of the primary jet-mix source changes with time. This requires a complete description of each source in terms of intensity, frequency, directivity, and distance, as well as a methodology for combining each noise contribution. It is felt, however, that for the purposes of this study such refinement is unnecessary, particularly in view of the fact that noise field prediction techniques are not well developed and the final aircraft configuration has not been selected. A simple model is desired which provides a fair representation of the noise sources and preserves the essential tradeoffs.

A model is developed which expresses PNL as a function of distance to the listener, thrust, and attenuation constants. The following assumptions will be made.

Assumption 1: Fan Noise

Since the fan provides flap air thrust, assume that the augmentor jet mix noise is of the same order of magnitude as the fan discharge jet noise; then the fan is the dominant noise source.

There are no accurate methods for the prediction of the acoustics of fans. Therefore, Ref. 5 suggests an average of three tentative prediction methods used in the field, given as:

$$SPL_o = 10 \log \dot{W} + 40 \log V_T - 34 \quad (B-1)$$

where

- SPL_o = 200 foot sideline maximum sound pressure level (includes both discrete tones and white noise)
- \dot{W} = weight flow rate through the fan
- V_T = tip speed of single stage compressor blade

Instead of employing the usual method of calculating PNdB from SPL (which involves extensive table look ups), Ref. 5 develops an approximate relationship (± 0.5 PNdB) which results in Eq. B-2, with \dot{W} and V_T maximum thrust values.

$$PNL_o = 7.5 \log \dot{W} + 47.5 \log V_T - 36.5 \quad (B-2)$$

where

$$PNL_o = \text{PNdB at 200-foot sideline distance}$$

Other fan noise prediction methods are given in Ref. 6. All predict the sound pressure level at a reference distance along the line of maximum radiation.

Assumption 2: Thrust Variations

Reference 5 expresses the reduction in fan noise due to partial power operation as

$$\Delta PNL = 25 \log (T/T_{max}) \quad (B-3)$$

where

$$T_{max} = \text{maximum sea level static thrust of the engine.}$$

For a turbojet compressor (i.e., bypass = 0)

$$\Delta PNL = 16.5 \log (T/T_{max}) \quad (B-4)$$

To test this relationship, PNL vs T/T_{max} was plotted for a typical engine in service today (see Fig. B-1). Since it is a low-bypass-ratio fan, we would expect a coefficient value near 16.5. The results shown in Figs. B-2 and B-3 indicate a logarithmic relationship for a low-bypass engine as anticipated. The thrust reduction law given in Ref. 5 appears reasonable for high-bypass engines.

Assumption 3: Atmospheric Attenuation Law

Computing PNL from SPL according to the standard method of Ref. 7 involves extensive table-look-ups. An expression has been developed in Ref. 5 which allows economic computer computation. The result relates the attenuated PNL to sideline distance H .

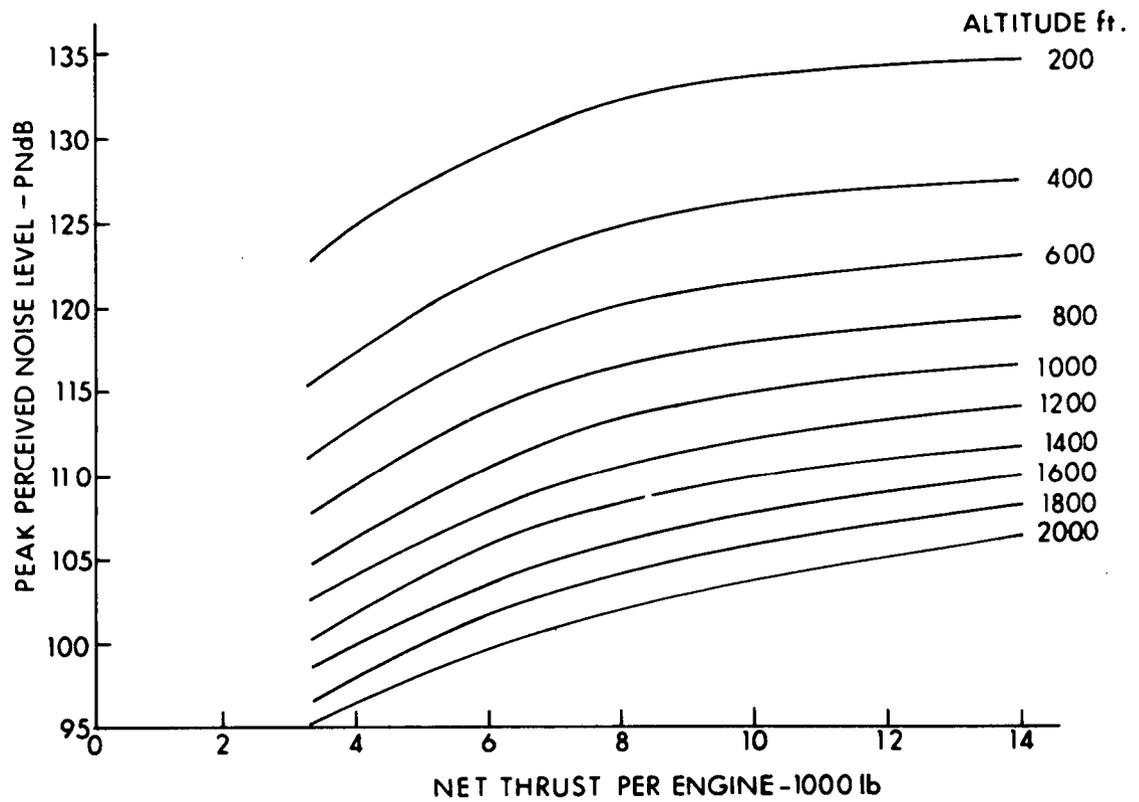


Figure B-1 Perceived Noise as a Function of Thrust and Altitude for a Typical Turbofan Currently in Service (Ref. 11)

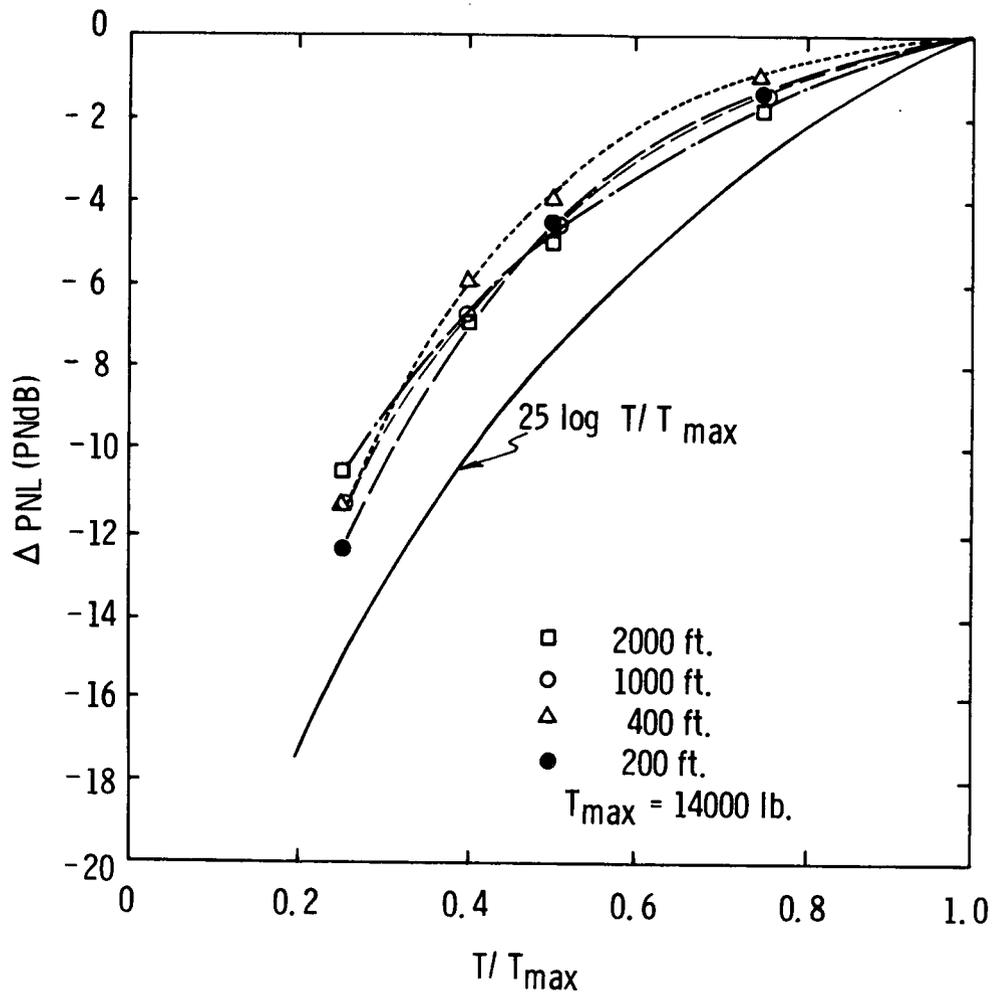


Figure B-2 Change in Perceived Noise Level as a Function of Thrust Level for a Typical Turbofan Currently in Service

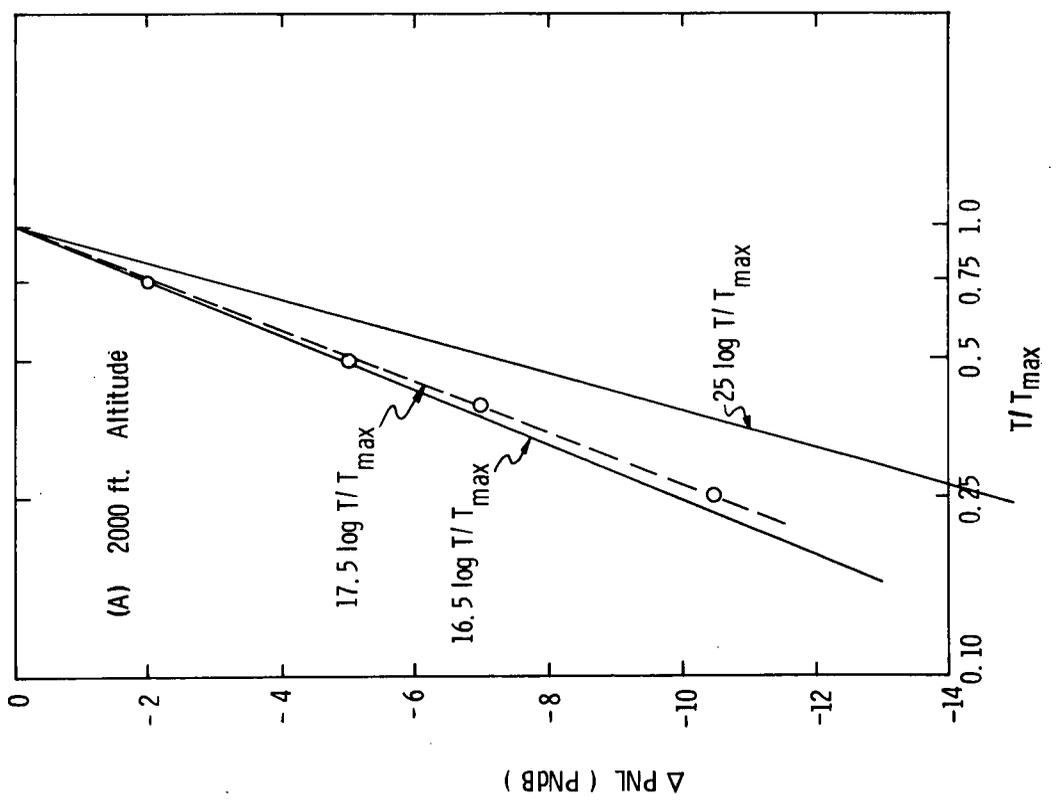
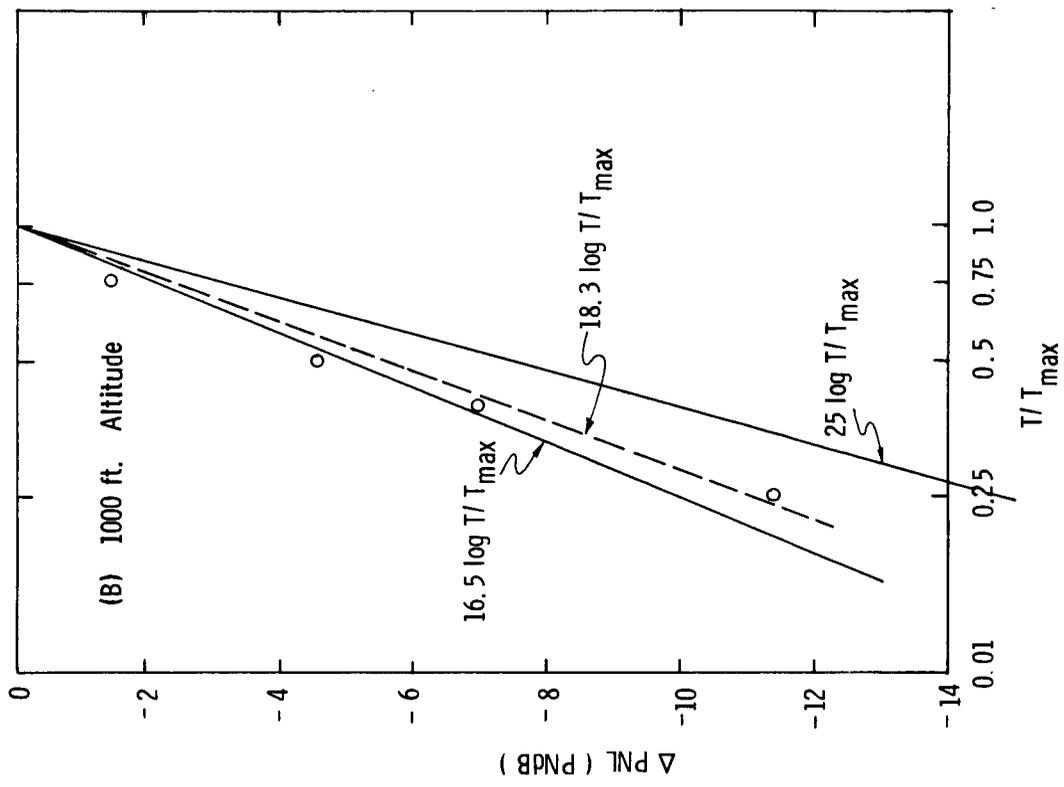
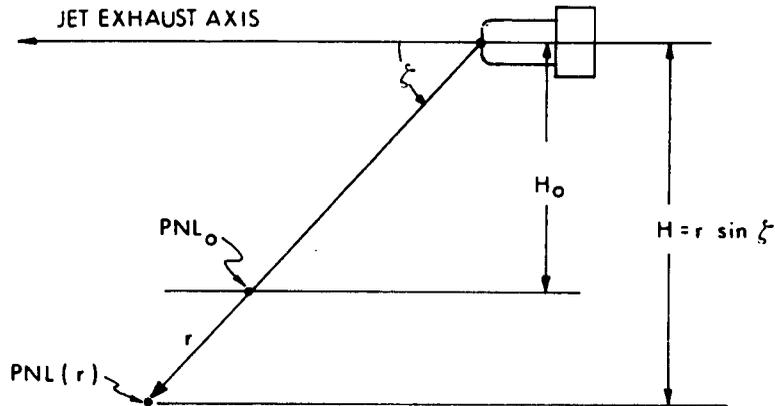


Figure B-3 Change in Perceived Noise Level as a Function of Thrust Level for a Typical Turbofan Currently in Service (Log Scale)



$$\Delta \text{PNL} = \text{PNL}_0 - \text{PNL}(r) = \alpha \log (H/H_0) + \frac{\beta H_0}{\sin \zeta} (H/H_0 - 1) + 1 \quad (\text{B-5})$$

where

$$\begin{aligned} H_0 &= 200 \text{ feet} \\ \beta &= \text{attenuation constant} = 1.069 \times 10^{-3} + 8.6148 \times 10^{-7} (f) \\ f &= f_0 \sqrt[3]{T/T_{\text{max}}} \quad , \quad f_0 = 2500 \text{ Hz} \\ \alpha &= 22.1056 \\ \zeta &= 90 \text{ deg} \end{aligned}$$

Figure B-1 was again used to check the validity of the relationship. The results are good to ± 1 dB.

Assumption 4: Spherical Radiation Law

Information describing the directivity of fan noise is not readily available. A conservative approximation is made by using a spherical radiation model that is based upon a reference noise level at 90 deg to the engine axis. Because fan noise is not highly directional, this is a good approximation at moderate aircraft altitudes.

The equations are:

$$\text{PNL} = \text{PNL}_0 + 25 \log(T/T_{\max}) - \{\alpha \log(r/200) + 200 \beta(r/200 - 1) + 1\} \quad (\text{B-6})$$

$$\text{PNL}_0 = 7.5 \log \dot{W} + 47.5 \log V_T - 36.5 + 10 \log N_e + g(\Delta_{J-C}) \quad (\text{B-7})$$

where

T = thrust generated by engine = $T_{\text{primary}} + T_{\text{fan}}$

$10 \log N_e$ = correction for N_e (number of engines)

$g(\Delta_{J-C})$ = correction for jet noise

For present noise modeling, rather than specifying \dot{W} and V_T for a turbofan engine to determine PNL_0 , we can assume a PNL_0 value for an advanced turbofan design. The goal of STOL engine noise output is 95 PNdB or less at 500 feet, thus the value of PNL_0 at 200 feet should be about 105.76. The result is:

$$\text{PNL} = 105.76 + 25 \log (T/T_{\max}) - \{\alpha \log(r/200) + 200 \beta(r/200 - 1) + 1\} \quad (\text{B-8})$$

B.4 STOL PROPULSION

Everyone seems to agree that the essence of a STOL system is quiet operation, and this means quiet engines. The first STOL vehicles to come into active commercial service will probably be 4-engine turboprop craft in the 50-70 passenger category. It appears that by keeping propeller tip velocities low (in the 600-700 ft/sec range) such vehicles may be able to achieve noise levels of about 95 PNdB at 500 feet.^{8,9}

Looking ahead to jet STOL craft it appears that new turbofan engine designs utilizing such features as high bypass ratios and variable-pitch fan blades may allow 80-150 passenger vehicles to achieve the required noise levels. These engines will merge some of the characteristics of propellers and present turbofans, such that they have been dubbed "prop-fans" by at least one source.¹⁰ They will achieve high bypass ratios (e.g., 20:1) by increasing fan diameter, and fan tip speeds will be kept to about 700 ft/sec (as compared to about 1,200 ft/sec in present turbofan engines). Their noise level can be kept low because of reductions in the two main sources of noise in present jet engines: (1) turbulent mixing of the high-velocity hot-gas exhaust from the combustion chamber; and (2) whine from the high speed fan blades. These sources are reduced because more energy is taken from the combustion-exhaust stream to drive the fan, thereby reducing the exhaust velocity, and the fan actually turns at a lower rpm, thus reducing the energy as well as the frequency of the tonal components.

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