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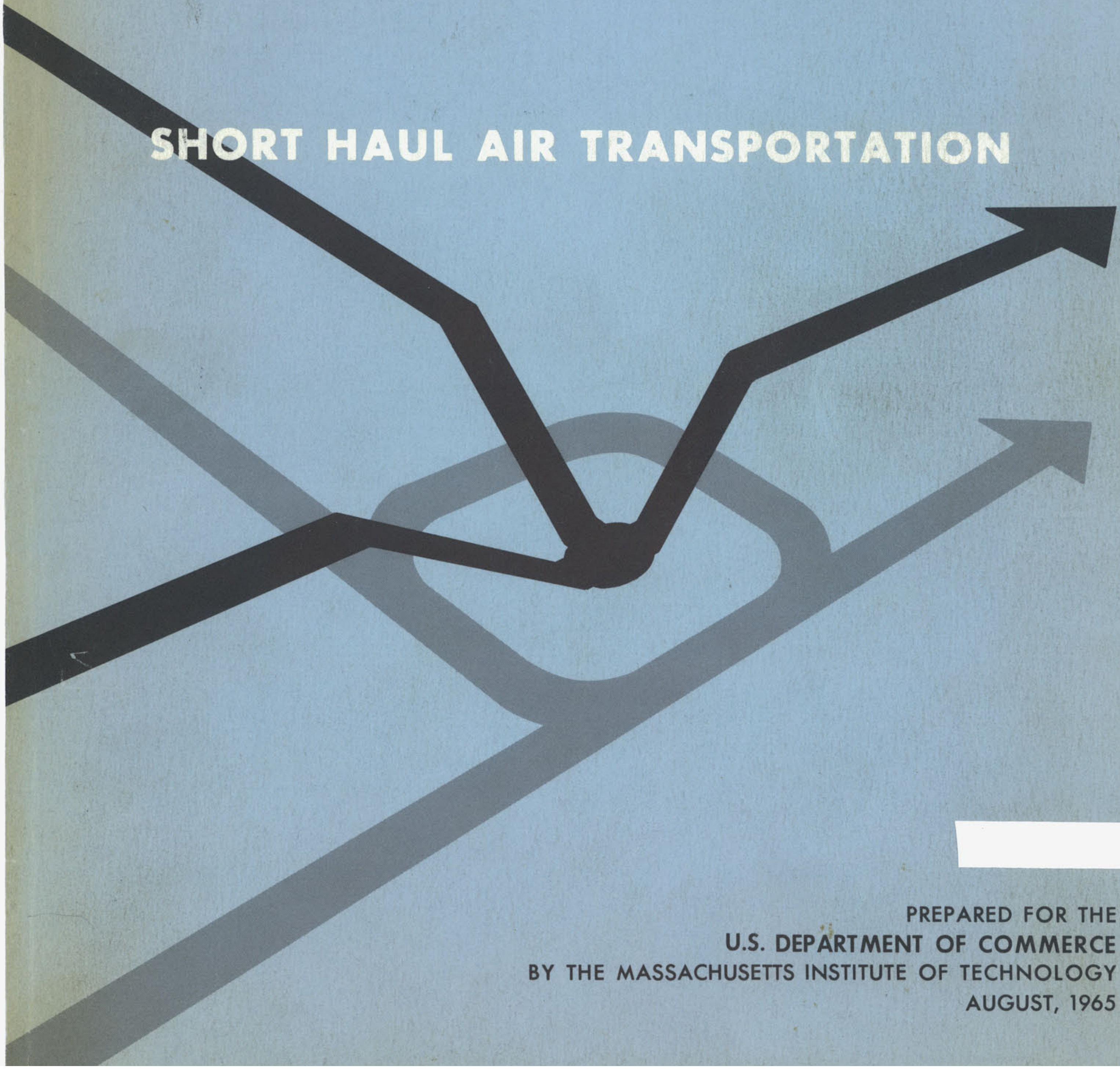
A SYSTEMS ANALYSIS OF

SHORT HAUL AIR TRANSPORTATION



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AUGUST, 1965

FTL 65-1

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Aeronautics and Astronautics

Continuation Of

A SYSTEMS ANALYSIS OF SHORT HAUL AIR TRANSPORTATION

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A SYSTEMS ANALYSIS OF SHORT HAUL AIR TRANSPORTATION

This program is concerned with the continuation of a study of short haul air transportation problems to establish the potential role of air travel using a systems approach in which all economic, operational, and technical factors are examined.

This work will be conducted in the Department of Aeronautics and Astronautics which is under the direction of Professor C. S. Draper. The work will be under the supervision of Professor R. H. Miller with the active participation of Professors Secor Browne, R. W. Simpson, and N. D. Ham.

INTRODUCTION

Work conducted to date at M. I. T. has resulted in a definition of the performance of several different types of aircraft over considerably shorter ranges than are usually considered for air transportation. The Direct Operating Cost has been determined as a function of range for helicopters, jet lift and tilt wing VTOL aircraft, short takeoff aircraft, conventional short and medium haul transports. As a result of these studies, it has become clear that air transportation has the potential of penetrating into a much shorter haul market than has usually been envisaged for this type of transportation. However, realization of this potential will require certain technological advances which are currently well defined on an experimental basis, but have yet to be reduced to general practice. In particular, implementation of current techniques for all-weather operations, a systematic reduction of VTOL aircraft maintenance costs, a more realistic approach to operations in heavily travelled areas, and a more flexible and automated approach to scheduling and general airline management could well result in air fares, even over short distances, which are competitive with current bus fares.

The current investigations have, as an end result, a first prediction of Direct Operating Costs as a function of range, utilization and load factors. These studies in addition are indicating the sensitive parameters and those areas requiring more intensive analysis. It is considered essential to continue the investigation in order to define more clearly the controlling factors which govern the behavior and costs of short haul air transportation systems. The areas of investigation which it is believed should be actively pursued are outlined in the following discussion. Additional areas of investigation which should be pursued in an expanded program are included as an addendum.

The time period envisaged for these investigations would cover a period of one year with an additional year for that portion of the investigation included in the addendum. If work were conducted for a shorter period than one year, the major effort would be placed on Item (1), Determination of Maintenance Cost Potential and Item (5), Navigation and Airspace Limitations. In considering a systems analysis of this nature, it is difficult to be more specific with regard to short term research.

DISCUSSION

1. Determination of Maintenance Cost Potential

Our studies of the Los Angeles and New York helicopter airways systems, which are the only extensive short haul air transportation systems currently in existence, have clearly indicated that maintenance costs are the major item determining the high seat mile costs of these operations. During the next few months, it is expected that the major items which determine this cost will have been defined and a reasonable prediction of the potential reductions in maintenance costs established. However, because of the very great amount of statistical data which is being uncovered in both the military and civilian systems, it is expected that further study of this important problem should be conducted in order to define more clearly those areas requiring intensive technological effort in order to reduce helicopter maintenance costs to the level of those experienced with the better fixed wing systems or to determine the minimum costs which may be realistically anticipated. It should be noted that at the present time maintenance costs for helicopters are of the order of 5 to 10 times those which are experienced on a comparable basis in other types of commercial air transportation. It is possible that these high costs are inherent in the type of operations or the environmental conditions required for intra-urban or city center type transportation. It is important that, if such limitations exist, they be exactly defined before any realistic prediction of the potential of air transportation inthe very short haul areas is attempted. It is expected that continuing study of this problem will result in a better definition of the potential maintenance costs, not only for existing systems, such as helicopters, but for other types of VTOL aircraft, as well as advanced helicopter configurations.

2. Indirect Costs Minimization

It appears that the indirect costs vary between 80 and 140 per cent of the direct operating costs and, therefore, are a major factor in determining ticket price. The source of these costs is directly tied to the system as it is presently conceived. This system has been developed primarily for long haul transportation and it is most important to examine, in the light of a short haul high frequency operation from a dense population center, what the optimum system leading to minimum indirect costs could be. Such a study would cover ticketing practices, scheduling, route selection, passenger handling, and maintenance techniques. It is believed that major changes in present airline management techniques will be indicated for short haul operations and that corresponding major reductions in indirect operating costs will result.

3. Interaction Between Vehicle Size and Market Size

The total costs of operating a complete air transportation system are heavily dependent on the size of the market to be served. The traffic density on a given set of routes determines the optimum vehicle size, the frequency of service, and the passenger load factor achieved, as well as utilization factors for terminal facilities and ground personnel. While the vehicle direct operating costs can be stated as functions of capacity, production run, and utilization, it is difficult to compare different vehicle designs until a clear specification of market demands are known. It is important, therefore, to examine possible service patterns for a very short haul air transportation system.

4. Multiple Mission Capability

A somewhat related problem is that of determining what methods exist for increasing utilization of short haul aircraft during off-peak hours. Many missions, other than the transportation of people, can be envisaged, particularly for VTOL aircraft, such as parcel delivery and general cargo handling, construction, surveying, agricultural work, traffic control, pipeline and powerline maintenance, and many others familiar to all non-schedule helicopter operators. The degree to which a commercial transport helicopter would be suitable for some of these missions will have to be determined and the feasibility of combining a regularly scheduled passenger transportation system with general utility operations established.

5. Navigation and Airspace Limitations

Although three-dimensional operations in the air permit a much greater density of traffic than can be envisaged for ground transportation over fixed rights of way, the airspace is not by any means unlimited. The extent to which this will be a limiting factor in commercial air transportation requires further definition. Clearly, this could be a limiting factor under certain instrument flight conditions, particularly in the terminal areas. However, modern techniques of air traffic control and on board navigation devices when fully developed will permit a much reduced separation both enroute and in the terminal area. Saturation of the airways is, therefore, unlikely but again, as in any system study, this factor must be related to the market size, optimum vehicle capacity, frequency of service, network distribution, and flight speeds. Although this study will be made in a preliminary fashion under the present contract, it is expected that continuing effort in this area is essential and in particular requires a better definition of the market size.

6. Terminal Area Control and Vehicle Design

It is impossible to examine the critical problem of control in a terminal area independently of the type of vehicle which is to be controlled. As a result of the studies outlined above, it is expected that this vehicle will have certain well-defined characteristics which may or may not be optimum for safe all-weather operations in a highly congested terminal area. Consequently, a further investigation of the interaction between vehicle characteristics, terminal congestion, and terminal area control is required. For example, certain VTOL aircraft, while capable of operation at very slow speeds, consume large amounts of fuel under these flight conditions. Others may be designed to operate with a high degree of efficiency down to practically zero speed, but, on the other hand, have serious high speed limitations. The dynamics of these aircraft also vary considerably with their flight speed and the stability and control characteristics must, therefore, be closely related to the proposed handling techniques. If a reasonably high degree of sophistication in the automatic control systems for these aircraft is assumed, then no serious problem will exist with any of the configurations to be considered. However, the definition of the degree of sophistication and the overall costs of such a subsystem will have to be defined as well as the probability of successful implementation in the time period being considered.

7. Ultra Short Haul, Intra-Urban Transportation System

Most transportation systems, whether ground or air, operate essentially from a single point in an urban center to another point and the distribution to and from these points is never very clearly defined or is presumed to involve some form of automotive transportation. In view of the fact that our studies to date tend to indicate the possibility of low operating costs for VTOL aircraft down to very short ranges of the order of 10 miles or less, it is entirely possible to conceive of a distribution system which includes some form of air transportation into the terminal areas. It is even possible to conceive of an area transportation rather than a point transportation system with several collection points in both the origin and destination areas some of which could themselves be directly linked. Such a system would require a high travel density in order to be feasible. Also, because of the random nature of the demand, it may be necessary to eliminate any fixed schedule, but rather establish a floating computer controlled schedule, whereby aircraft would be directed to pick up at any point where a sufficiently large demand had accumulated. The system could operate with certain constraints such as a maximum wait time of 15 minutes for any passenger or a maximum number of stops for any one passenger of say 2 or 3 in going from one point to another in the two urban areas. It is considered worthwhile to examine the feasibility of such a system once a better definition of the market has been established as both a means of feeding into a central terminal area and as a means of providing an alternate direct non-stop or single stop transportation from suburban points in one area to suburban points in another area.

Concluding Remarks

Examination of the above areas of investigation proposed for a continuing study of the potentials of short haul air transportation emphasizes the importance of examining this problem as a system with many closely interrelated subsystems, each of which is heavily dependent on the others. In the past, commercial air transportation has developed largely as a result of advances in technology stimulated by the requirements of military weapon systems. This is particularly true for the flight vehicle where increases in speed and performance have been the dominant requirements of both the military and civilian systems, but it is also true, although to a lesser extent, for many of the other subsystems including navigation and control. Borrowed technology has thus been patched together into a system which, while not optimum for its primary function, at least makes use of advanced technology without having had to assume the cost of basic research and development. It is expected that commercial air travel will continue to benefit from military sponsored technology; however, the industry has now grown to the point where consideration should be given to determining the optimum rather than the most expedient air transportation systems and defining the technological steps which could eventually lead to this optimum system. Such a study should be conducted on a continuing basis and with increasing depths as research indicates those areas requiring more intensive effort.

ADDENDUM

EXTENDED STUDIES OF SHORT HAUL AIR TRANSPORTATION

The outline of studies proposed above for a continuing investigation of the short haul air transportation covers only those items which are believed to be essential for conducting a parametric investigation of the problem, particularly as it may relate to other forms of transportation. However, there are several additional items which could well be investigated if time and funds permit. These are briefly outlined below:

1. Mechanization of Flight Control Systems

There are currently under investigation at M. I. T. several flight control systems whose intent is to increase the capability of aircraft for operation under all-weather conditions. It is important to extend these investigations to cover the determination of the exact mechanization which would be required in order to provide a completely reliable all-weather IFR capability in a highly congested airways system. This would involve the exact definition of the sensors, whether inertial, doppler or radar, the method by which such systems would be coupled into the control system for the aircraft, which in turn will depend heavily on the aircraft configuration, and the interface between the aircraft and the ground controller, as well as the degree of automation which would be desirable at both control points. Although the studies which are currently being conducted at M. I. T. cover certain of these factors, they are influenced primarily by the military requirements of the sponsor or other considerations not directly related to the operation of a high density transportation system, such as is envisaged in this case.

2. Effect of Environmental Factors

It is believed that the environmental conditions peculiar to any area are important in determining the optimum characteristics of air transportation systems. For example, the Eastern Corridor is primarily a sea level type of operation. It is, therefore, desirable to extend this study to other areas, in particular involving mountainous terrain, or high level operations, where high temperatures may be anticipated and otherwise to consider the impact of area characteristics on any air transportation system.

3. Foreign Market Potentials

It is also considered desirable to extend this study to a survey of the potentials of other than U. S. type markets for such an air transportation system. If it is believed suitable for, for example, Western Europe, particularly in the highly populated areas of Belgium, Northern France, and England, as well as Western Germany, then a very large market potential exists for any particular aircraft which, in turn, could result in a major reduction in the systems cost.

4. Sociological Impact

A high speed transportation system operating intra-urban will certainly have a major impact on community decentralization. If speeds are increased by an order of magnitude and, hence, transportation times reduced accordingly, it may be expected that decentralization will occur in some proportion to the reduction in travel time. The resulting reduction in population density will in turn have a major effect on the transportation system and could be self-defeating unless the secondary transportation links grow accordingly. Similarly a major change in distribution and retail sales concepts may occur. It is essential to examine these factors carefully in order to determine whether any system being considered will have a high rate of obsolesence.

5. Advanced Technological Concepts

Aerospace technology advances rapidly under the stimulus of military requirements and space exploration. New propulsion techniques are being developed almost more rapidly than they can be assimilated. New techniques of flight guidance and new methods of airframe and engine construction are developing rapidly. In general, these tend to a higher degree of reliability, reduced maintenance, and, in particular, in reduced weights. Weight reduction has a major effect on the direct operating costs and, hence, the system effectiveness. For example, a new technique of construction utilizing high strength boron fibers is currently under development which may result in a reduction in structural weight for aircraft of as high as 50 per cent with possible lesser reductions in propulsion system weights. This may result in a doubling of the payload and, hence, a major reduction in direct operating costs. It is necessary to assess carefully these technological developments and determine to what extent they may be expected to be applicable in the time scale considered for the present investigation. Neglect of these potential advances could result in a major error in predicting the potential of air transportation for the future. While the difficulty of defining with any degree of precision the advances in aerospace technology is recognized, certainly an attempt should be made to include the effect of those advances which can be reasonably anticipated in any study of this nature.

Concluding Comments

As in all research, it is difficult to determine which avenues could be most fruitfully pursued ahead of time. As our investigations continue, it is more than probable that new areas requiring further study will be clearly indicated and the scope of this investigation should, therefore, be planned on as board a basis and with as few constraints as time and funds permit.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
FLIGHT TRANSPORTATION LABORATORY
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A SYSTEMS ANALYSIS OF SHORT HAUL AIR TRANSPORTATION

Part III of a
Report under
U.S. Department of Commerce
Project Transport

Contract No. C-85-65

CONCLUSIONS

1) A short haul air transportation system for the Northeast Corridor could be developed during the 1970-80 period for a total investment of the order of 0.5 billion dollars and operating at fare levels of the order of 5 cents per passenger mile over stage lengths around 100 miles.

2) This system would have an improved all-weather capability which would permit operation under 99.5% of expected weather conditions and would show a trip completion factor at least as good as present ground transportation systems.

3) The direct operating cost differentials between VTOL, STOL, and conventional short haul aircraft are not sufficient to be decisive in the choice of any particular vehicle type.

4) The indirect costs are, however, a dominant factor in determining choice of vehicle type and would indicate a preference for aircraft with a complete vertical takeoff and landing capability because of the greater convenience in siting and lesser terminal costs in city centers.

PREFACE

This report has been prepared in the M.I.T. Flight Transportation Laboratory under the supervision of Professors R. H. Miller and R. W. Simpson, with contributions from H. A. Fitzhugh, J. F. Fort, R. A. Gallant, G. B. Katz, J. D. O'Doherty, C. H. Pearlman, M. P. Scully, and C. M. Wooten. It forms Part III of a series of reports in a research planning study carried out by the Massachusetts Institute of Technology for the NORTH EAST CORRIDOR TRANSPORTATION PROJECT of the United States Department of Commerce. The authors wish to express their appreciation to the many personnel from airframe and engine manufacturers and the airline operators who contributed so generously of their time and gave access to various detailed information as background for this study.

Other reports prepared by M.I.T. under this contract are:

Part I	Survey of Technology for High Speed Ground Transport
Part IA	Bibliography of High Speed Ground Transport
Part II	High Priority Research Tasks for High Speed Ground Transport
Part IV	Cost Methodology and Cost Models for High Speed Ground Transport

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A SYSTEMS ANALYSIS OF SHORT HAUL AIR TRANSPORTATION, PART III

August 1965

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PART I

INTRODUCTION AND SUMMARY

INTRODUCTION

The study presented in this report is concerned with establishing the potentials of air transportation in the 1970-80's as related to the transportation demands in the Northeast Corridor.

A complete systems analysis has been undertaken, including the determination of optimum vehicle characteristics, estimation of future direct operating costs, management information requirements, scheduling and ground facilities, leading to an estimate of the indirect costs of operating a short haul air system, and the possible fares and travel times. The total system capital investment in vehicles, terminals, navigation equipment, maintenance facilities, etc., has been estimated. Current values in 1965 dollars have been used in this report. Advanced concepts of engines, aircraft and computer technologies anticipated for the 1970-80 period have been taken into consideration in the analysis.

Whether air transportation or any other form of public transportation can capture an appreciable portion of the short haul market is open to question. At the present time, this market is dominated by the automobile which satisfies over 90% of the travel demand. The door-to-parking lot flexibility of the automobile and its low out-of-pocket expenses, of the order of 2 to 3 cents a mile, together with its flexibility and efficiency as a very short haul transportation vehicle, make it a preferred method of transportation.

Against this competition, air transportation can offer an order of magnitude increase in speed (see Figure I-1). Furthermore, with the newer concepts of vertical takeoff and landing aircraft, it can also offer a degree of flexibility which is exceeded only by the bus. With no need for right of way or elaborate terminal facilities, an air transportation network can readily adjust to the short term cyclical changes in demand and to the longer term population shifts.

These advantages must be evaluated in terms of cost and reliability and it is with these factors that this report is primarily concerned.

The system concept which has evolved in this report may be described as VTOL Airbus Transportation system, serving all major cities in the Northeast Corridor either at present airports, or at city center or suburban sites. Multistop flight segments would be flown with intermediate stopping times of the order of 3 minutes and an average vehicle hop below 100 miles. A high frequency of service would be maintained with flexible scheduling to match demand variations throughout the year. A high degree of operational reliability can be achieved by using automatic equipment to stabilize and guide the VTOL vehicles, and designing air traffic procedures which are independent of fixed wing procedures.

The technology exists for providing an all-weather capability which, at least for VTOL aircraft, will equal that of any other existing transportation systems and this capability will almost certainly be operationally available in the time period considered in this study. The omnidirectional approach capabilities of VTOL aircraft also appear to eliminate any problem of V/STOL air traffic congestion in the terminal area.

City center terminals would be specially designed for rapid processing of passengers and vehicles. A very low cost suburban stopping point can be easily sited to distribute the passenger loading points wherever sufficient demand exists. Reservations and baggage handling would exist to interface with the airline system, but except at peak times, the ordinary traveller would be able to board on a standby basis.

In general, the VTOL airbus system will be economically competitive with present transportation by 1980 with the typical trip times and trip costs shown by Figures I-1 and I-2 respectively.

The direct operating costs of all VTOL vehicles are better than 1980 conventional aircraft for distances less than 100 miles, and the system indirect costs are similar to present helicopter costs with some improvement due to increased system size. The low system investments as shown in Table I-1 and the flexibility of the system in response to demand, both in area coverage and cyclic variations throughout the year, make the VTOL Airbus system an attractive solution to the growing transportation requirements in a megalopolis, such as the Northeast Corridor.

The cyclical nature of travel demand with peaks occurring daily, weekly, and seasonally, remains a major problem in realizing effective utilization of both vehicles and terminal facilities. Much study of optimum management systems will have to be conducted before this well known transportation problem is solved. The problem is a common one to all forms of transportation having relatively short trip times, whether rail, bus, or air, and will exist even for the supersonic transport travelling the Atlantic route. No easy solution is apparent at the present time, although the possibility does exist of maintaining utilization high with air transportation by providing a high speed freight or package delivery service at off-peak hours and utilizing the vertical lift capability of the aircraft for a multitude of tasks.

The growing congestion of ground transportation and the tendency to charge the automobile with the cost of the roadways and terminal facilities, so that its true operating costs become apparent to the user, will certainly force the short haul market to search out better methods of transportation. Whether the convenience, speed, low cost and comfort of air transportation will make this a preferred mode of travel in the next decade, is impossible to say at the present time. The purpose of this report is simply to present the predicted direct operating costs and all weather capabilities of several types of air vehicles projected into the 1970-80's and to prepare an estimate of the possible fare structures and capital investments involved. A brief study of travel demand has been made in order to provide guidance as to vehicle and terminal sizing. The results are essentially based on an extension of existing airline service including a reservation system. It is possible that the demand in the period under question could be much greater and include an appreciable portion of the present automobile travel. However, the conclusions reached have been found to be relatively insensitive to the absolute market size and pending further information on present travel demand, no attempt has been made to extend this study to include a larger market than the present estimates of air travel demand, or to a minimum cost, no reservation bus type system.

The report has been divided for convenience into seven sections dealing with the vehicles, the direct operating costs, the estimated demand, the terminal facilities, the management systems, the indirect costs, and finally the all weather capabilities. Needless to say, all these elements are heavily interacting. The results are presented in the form of direct operating costs (DOC) as a function of stage length. DOC has proven to be a convenient measure of effectiveness for air systems because almost all controllable elements are included in this factor. The indirect costs, which on present air transportation systems are about equal to the direct costs, have been more difficult to project. However, estimates of these costs have been presented for a system which provides the same level of service, including reservations, expected by the present day air traveler.

A discussion of the results obtained is presented in the following pages.

DISCUSSION OF RESULTS

Vehicle Design

Typical direct operating costs and block times for the tilt wing, jet lift, advanced helicopter, and STOL vehicles studied in this report are shown in Figures I-2 and I-3. No determination of the preferred size or type of vehicle can be made until some indication of predicted demand is given. In general, for all the VTOL and STOL aircraft, direct operating costs below 2 cents/available seat mile can be expected over stage lengths between 50 and 200 miles. Advances in technology during the 1970's can potentially result in DOC's below 1 cent/available seat mile for a system operating after 1980 (Figure I-4).

Comparison of vehicle costs alone shows that the 1970 conventional jet transport, and the jet lift V/STOL are very comparable and will have better unit costs than other vehicles for trip lengths over 100 miles. For trips under 100 miles, the tilt wing and helicopter use their block penalty advantage to maintain unit costs below 3 cents/available seat mile. The STOL, with its block time penalty, has higher unit costs for the shorter ranges.

Optimization of both STOL and VTOL aircraft for the specific mission being considered here has indicated very little weight penalty for providing a full VTOL capability when all factors in the design are considered. This result, which is contrary to most experience with military VTOL predictions, arises primarily from the fact that the VTOL aircraft used here are point designs optimized for short haul transportation missions. The fuel capacity can be designed for short range only with a minimum of reserves. Also, it is not necessary, as in military aircraft, to design for a high degree of maneuverability in order to achieve air superiority in combat or to permit evasive maneuvering near the ground. Furthermore, a VTOL with an STOL overload capability is not applicable to commercial transportation where certification is based on one maximum gross weight. Consequently, the wing area can be designed for optimum cruise; hence, at reduced fuel for climb and reduced wing weights, thereby partially compensating for the extra weight of the greater installed power. The STOL aircraft considered in this study on the other hand must have reasonably low wing loading to permit takeoff in the 1,000-foot distances assumed which forces cruise at off optimum conditions for the very short hauls considered in this study. Conventional aircraft will have excellent direct operating costs on the longer ranges, below those which can be reasonably predicted for VTOL or STOL, but they pay an even greater penalty at the shorter ranges for the increased ground and air maneuvering times (Figure I-3).

Several assumptions have been made in the analysis of the vehicle direct operating costs which have resulted in what might be considered conservative estimates. For example, the provision of an engine-out hover capability without allowing for an emergency engine rating, no allowance made for technology improvements which would result in reduced structural weights and others as discussed more fully in Part II. When less conservative assumptions are made, including technological improvements leading to reduced maintenance costs, the DOC is reduced as shown in Figure I-4.

The prediction of future technological advances is to a great extent a matter of judgement and opinion and certainly open to question. A complete parametric analysis has, therefore, been conducted as part of the determination of vehicle characteristics and the effects of all basic assumptions presented in Part II in terms of DOC vs. stage length.

Direct Operating Cost Analysis

Maintenance is one of the most important factors in predicting the DOC of VTOL aircraft in the 1970-80 period. A careful evaluation of the maintenance costs with the only existing VTOL aircraft, the helicopter, in operation at the present time indicates that these costs are an order of magnitude greater than the costs for fixed wing aircraft. In an attempt to define the reasons for this cost increase, an investigation was made of the systems cost for fixed wing aircraft as experienced by the major airlines for comparison with the corresponding cost breakdown of the helicopter airlines. This type of information is not readily available for either type of aircraft. However, from the limited data available, it was found possible to arrive at a reasonable prediction of maintenance costs for the time period under consideration. Much work remains to be done in this area, but it is believed that if a reasonable technical evolution of the aircraft is possible, based on systematic redesign as dictated by maintenance experience, and if necessary development funds are expended in preliminary testing and field evaluation, then the maintenance costs used in this analysis are achievable.

Analysis of the 1960 ATA formula indicated that it is reasonably accurate in predicting present jet transport direct operating costs and predicts present helicopter transport costs with the only exception being the maintenance costs. These high costs appear to result primarily from the present level of helicopter services and design experience with commercial helicopter transports, and there were no reasons to believe comparable costs could not eventually be achieved. However, for VTOL aircraft, extraneous systems not found in conventional jet transports and requiring considerable maintenance and inspection, such as rotor, shafting, transmissions, etc., would always incur an extra maintenance cost penalty.

An important assumption in costing the VTOL aircraft was that the vertical takeoff and landing capability could be translated into reduced block time penalties which are very important in making an economic short haul air system. While operational experience with STOL aircraft is not available, the experience of present helicopter operators indicated that present helicopter services do have very small block time penalties. Since VFR conditions exist for more than 90% of the time, no traffic delay penalties have been assumed in estimating DOC.

One surprising result of this study was the degree to which speeds of the order of 400 miles an hour were still desirable for stage lengths of the order of 50 miles or less if a point-to-point transportation system could be assumed operating directly from one passenger loading ramp to a corresponding ramp at destination.

Transportation System Studies

Until good estimates of 1970-80 intercity passenger travel in the Corridor are available, the precise schedule of services, frequency of services between cities, vehicle utilization, optimum vehicle size, the size of ground facilities, and the system costs and fares cannot be determined. However, it is clear for an air system operating between all cities in the Corridor that the average flight segment will be less than 100 miles, and that increased frequency on the shorter segments will cause the distribution of flight segments to be heavily concentrated under 50 mile stage lengths.

With the low fares indicated by Figure I-2, the air system has a very large potential Corridor market, but the high productivity of the VTOL vehicles limits the fleet size required to the order of 100 aircraft. Other markets in the U.S.A. and Europe exist for these aircraft.

It is obvious that the air system can provide direct non-stop service at high frequency between all cities in the North-east Corridor, and can respond to growing demands by easily adding new stopping points, larger vehicles, and higher frequency of service. By stopping at airports, city centers, and suburban sites, it provides an interface with the dominant form of long haul common carrier, airline transportation, solves the airport to city center transportation problem, and distributes the air system pickup points over a greater area within the Corridor. With no need for right of way, or elaborate terminal facilities, an air network can readily adjust to short term cyclical changes in demand as well as longer term population shifts.

Ground Facilities

At the same site, STOL terminal facilities will cost between 3-4 times as much as an equivalent VTOL site because of the cost of extra land area required for runways. This larger area makes siting problems more difficult in city center areas, and increases the indirect costs for vehicle and passenger handling by 50% in the STOL system. A very low cost, minimal stopping point of roughly 2 acres is feasible for the VTOL Airbus system allowing introduction (or elimination) of service at various suburban sites. For vehicle sizes less than 100 passengers, the maximum stopping time required is less than 10 minutes, and average stop times of 5 minutes can be expected. A major investment in terminal buildings and passenger handling facilities will be required at the larger terminals to achieve these times in an efficient manner. Roof top operations from the VTOL terminal building can be expected in city center areas, and, in general, sites with suitable clear approaches and free from noise problems can be found in waterfront, expressway interchange, or railroad yard areas.

Management Information Systems

With the future development of computer hardware and software from the present airline reservation systems, it will be economically feasible to provide real time loading control, reservations systems, scheduling control, for efficiency in systems operations, and good data for marketing and management planning. This type of computer system will be necessary in achieving high employee productivity and low indirect operating costs, and in insuring good utilization and load factors for the air vehicles.

Indirect Operating Costs

For very short haul transportation systems, the indirect operating costs of the system become dominant over direct operating costs in determining the trip cost. Present airline indirect costs are much too high to compete successfully with surface transportation, and analysis of present helicopter and intercity bus carriers costs indicates what can be accomplished by truly short haul systems. It is of extreme importance to achieve low levels of station operation costs in terms of $ per passenger and $ per vehicle departure since a relatively larger number of departure and passengers will be handled by the short haul system. With a VTOL airbus system handling the large volumes of passengers anticipated by this report, using the mechanized large terminals to provide efficient and fast passenger boarding and the real time computer information system to insure high ground employee productivity, the projected Airbus indirect costs are roughly comparable to present helicopter system costs; i.e. about 1/5 airline costs, but still roughly double intercity bus system costs (see Figure VII 6). Ideally, indirect costs of about the same level as on bus systems could be achieved. However, this may not be possible when all the required safety provisions of air transportation are satisfied without a serious curtailment of passenger service amenities. Recent experience in the Western air shuttle service between Los Angeles and San Francisco indicates that fares approaching those of buses ($12 for the air shuttle versus $9.20 for the bus one way) are possible under the right conditions of demand and range. The indirect costs which are presented here are for a reservation system derived from existing airline experience modified to include a computerized scheduling based on demand. These costs could possibly be reduced for a minimum service commuter type non-reservation system. However, no estimate of this potential reduction has been prepared in this report, pending further information on demand.

Operating Characteristics of the Airbus System

By using automatic stabilization and guidance systems presently under development for military missions, V/STOL vehicles will have excellent handling qualities which will allow reliable, all-weather service almost independent of weather conditions. Operational reliability of the order of 99.5% should be obtainable with only severe storms and winds in excess of 50 miles per hour causing an interruption of service. Complete lack of visibility due to fog, snow, or the presence of freezing rain or sleet which in the past have curtailed surface transportation systems will not prevent the VTOL system from safe operation. Blind landing using good navigation systems and high intensity lighting for visual touchdown will be less of a problem than that currently being solved for fixed wing aircraft. By dispersing landing sites in metropolitan areas, and by insuring sufficient IFR takeoff and landing capacity, bad weather V/STOL operations without serious delays can be provided in congested airspace areas, such as New York, if the fixed wing traffic patterns and procedures are adjusted to allow segregated V/STOL operations. This will unload present ATC facilities and airports by redistributing some of the short haul air traffic in the Corridor.

Total System Investments

The total investments for the hypothetical Airbus System are summarized as requested in Table I-1. The unit cost of the 80 passenger air vehicles and the required fleet size are listed below:

Vehicle	Price ($M)	Required Fleet Size
Tilt Wing	3.83	65
Jet Lift	2.83	60
Helicopter	2.84	120
STOL	2.52	120

The tilt wing aircraft has been selected to determine typical VTOL vehicle investments.

Ground Handling Equipment is zero for the air system since the terminal design has included costs for hydrants, electricity, etc. to be installed at each parking pad. No ground vehicles of any sort are necessary in the Airbus system.

Terminal facilities are taken from Part V on System Ground Facilities. The VTOL A1, and the ground level, 1,000 foot STOL

Total Airbus System Investments

Category	Investments ($M)	
	VTOL	STOL
Air Vehicles - VTOL (Tilt wing)	250.0	
- STOL		303.0
Ground Handling Equipment	0	0
Maintenance Facilities		
- Hangars	3.2	3.2
- Airframe Overhaul Base	12.0	12.0
- Engine Overhaul Base	2.0	2.0
Terminal Facilities		
- VTOL System	93.1	
- STOL System		175.0
Controls	0	0
Land - VTOL System	89.2	
- STOL System		357.0
Headquarters Building and Computer System	30.0	30.0
TOTAL SYSTEM INVESTMENTS	479.5	882.2

TABLE I-1

terminals are used.

There are zero investments listed under controls since \$150,000 per vehicle, and \$250,000 per station have been included in the vehicle and terminal investments. The enroute Air Traffic Control System costs have been ignored, since it is assumed that existing government furnished systems will be covered by user taxes. The land costs are taken from Part V for the VTOL and STOL systems.

The headquarters building and computer system investments are taken from Part VI for the 20 million passengers per year system.

The total air system investment is less than 1 billion dollars. The VTOL Airbus concept is less than 0.5 billion, and is roughly one half an equivalent STOL system investment.

Future Research Investigations

The studies of this report have indicated the feasibility of a VTOL Airbus system for the Northeast Corridor. There are a number of critical areas where much effort and development is necessary in order to bring such a system into existence.

In most cases, the necessary research has been accomplished and in some cases the development stage has been finished or is being carried out by government agencies. Very little actual operational experience with such a system exists. The only close examples are the present urban helicopter carriers whose experience and operating information has been a valuable input to this report.

There are a number of promising areas of further investigation. Design optimization should take into account a number of off-design points, such as multiple stop flight segments, operating at off-design altitude or speed due to weather or traffic, the effect of different climb and descent schedules, etc.

A further detailed breakdown of maintenance costs for rotor and transmissions is necessary to establish a firm basis for predicting VTOL costs.

The possibility of incorporating a commuter service for large corridor cities using VTOL vehicles, such as the helicopter, operating from terminals common to the intercity service. With no baggage, or reservations, credit card billing, and common management maintenance and terminal facilities, it may be possible to produce indirect costs comparable to bus systems.

The network studies can be extended to produce schedules by time of day, and study the effects of demand or system size on vehicle selection and costs. When demand data is available, schedules and fares can be produced for the modal comparison by the National Bureau of Standards.*

The problems which will be encountered in making terminal area airspace available in areas, such as New York, need further definition and study. Technological developments in fixed wing aircraft navigation, guidance, and control, in future development of the air traffic control system, as well as operational developments in the present air traffic system need to be carefully studied in order to indicate the feasibility of all-weather, small delay IFR operations. Historical weather conditions in the Corridor should be gathered to define more precisely the operational reliability for given vehicle and system capabilities.

*A computer simulation is being carried out by the Bureau of Standards to compare the effectiveness of various transportation systems for the Northeast Corridor in 1980.

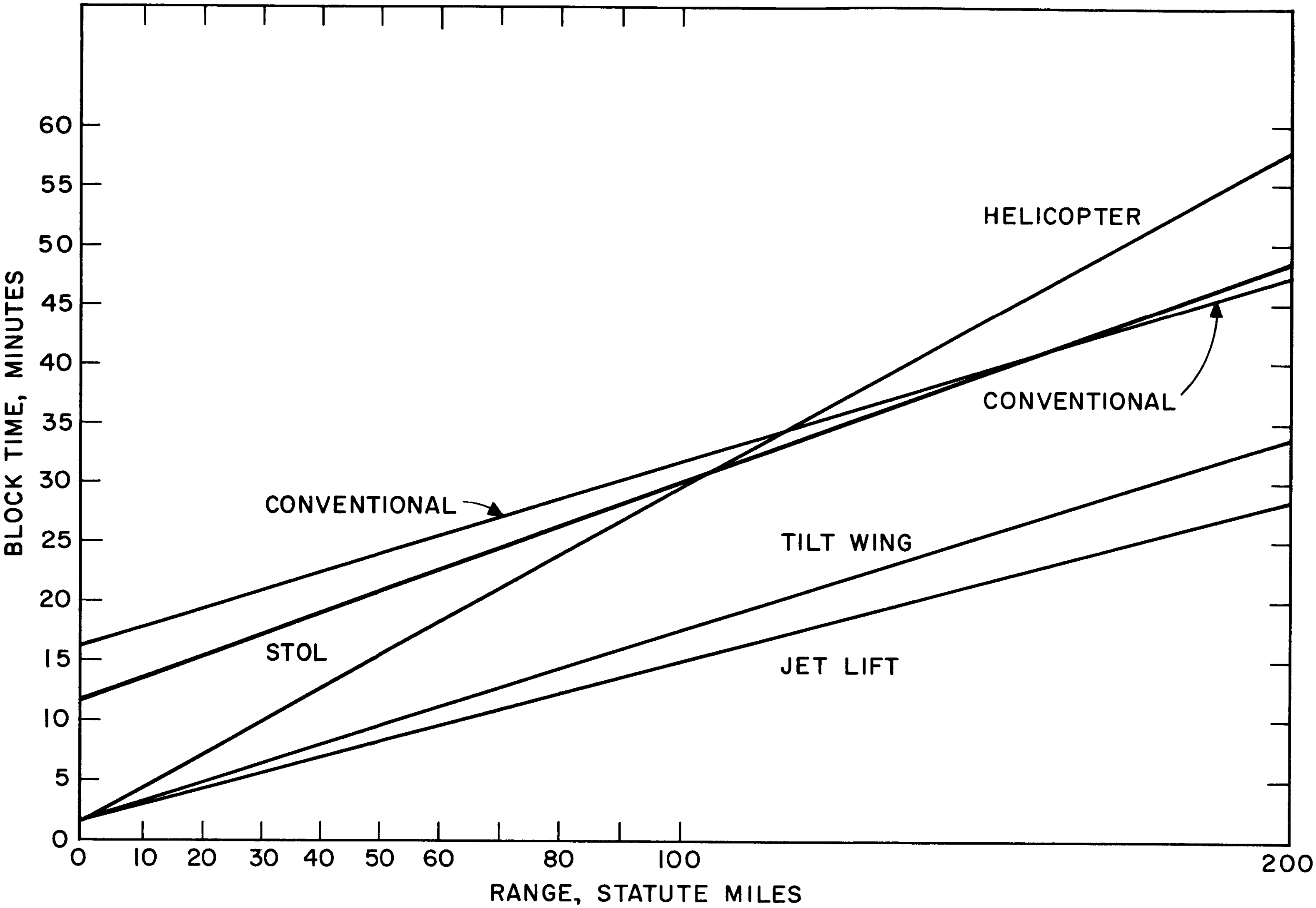

Figure I-1. BLOCK TIME AS A FUNCTION OF STAGE LENGTH FOR TYPICAL SHORT HAUL AIRCRAFT

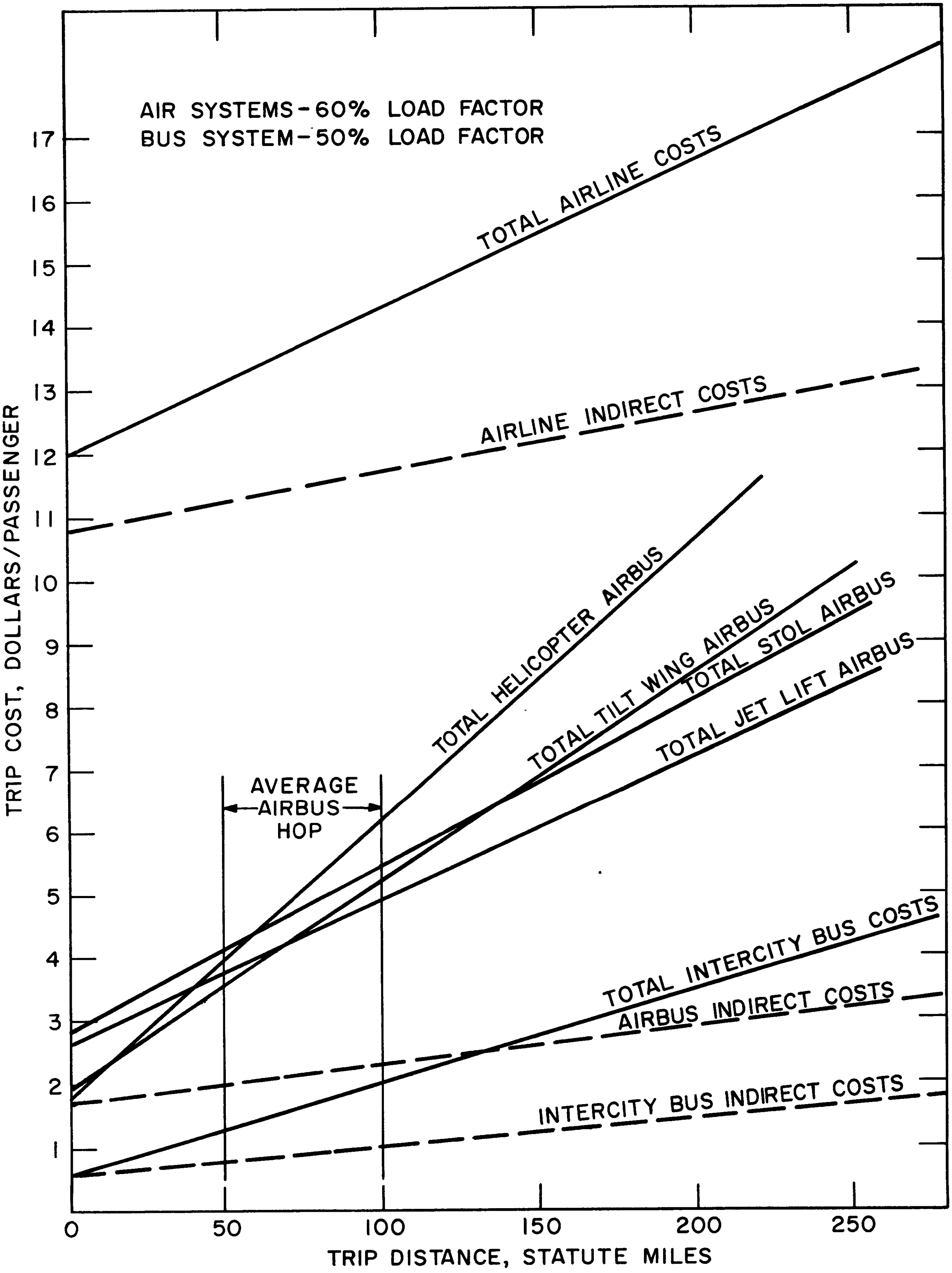

Figure I-2. TYPICAL TRIP COST PER PASSENGER vs. TRIP DISTANCE

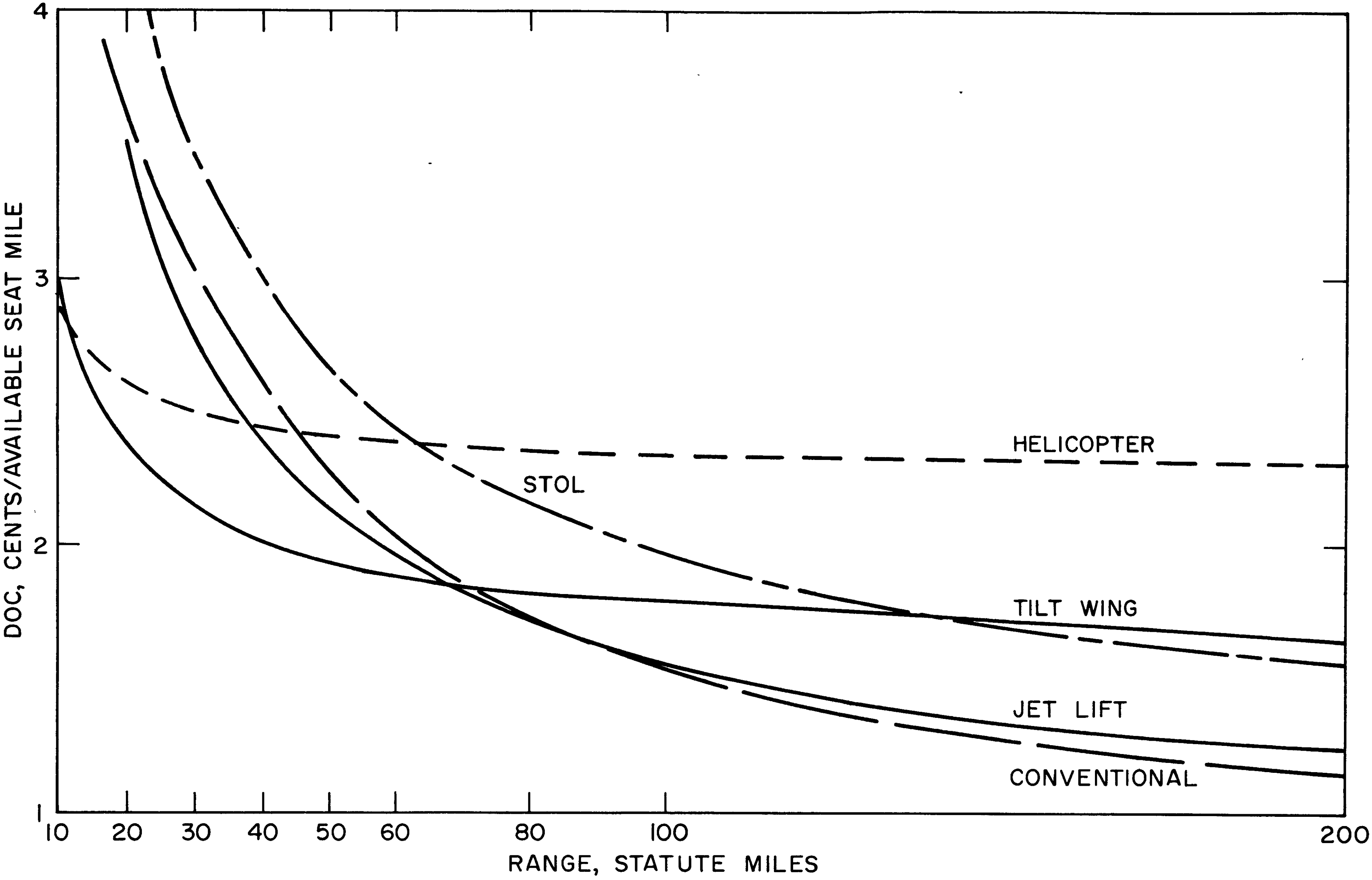

Figure I-3. DIRECT OPERATING COSTS FOR TYPICAL SHORT HAUL AIRCRAFT-1970 TIME PERIOD

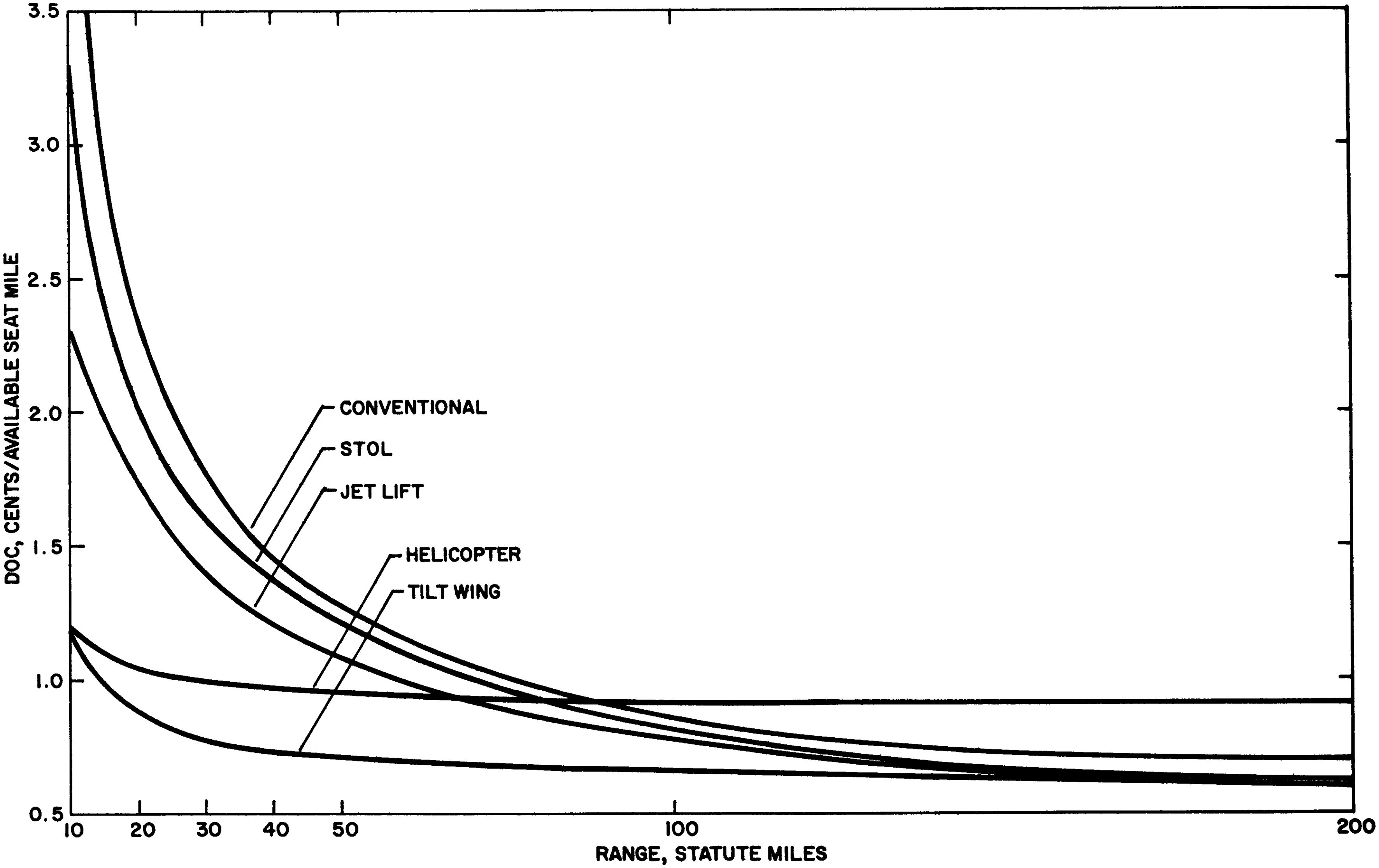

Figure I-4. DIRECT OPERATING COST FOR TYPICAL SHORT HAUL AIRCRAFT —ADVANCED TECHNOLOGY, 1980 TIME PERIOD

PART II

VEHICLE DESIGN STUDIES

II
TABLE OF CONTENTS

INTRODUCTION

In this section, the methods used for predicting vehicle performance characteristics are discussed in detail. These performance characteristics are, essentially, the fuel burned in completing the flight profile and the empty weight of the aircraft. With each vehicle configuration, the performance parameters, such as flight speed and cruise altitude, are optimized for minimum direct operating cost. The basic aircraft design parameters, such as wing loading and installed power or thrust, are in turn established by this optimization procedure.

Several types of vehicles were considered in this study, including a jet lift, tilt wing, STOL, various helicopter and compound configurations, and a conventional short haul jet transport. It was felt, however, that four types covered the spectrum of aircraft suited to the mission prescribed in this study and, therefore, the major studies were conducted using the first three and a conventional helicopter. On all of these aircraft various design studies were carried out using the time sharing facilities made available by the MIT Computation Center. This process makes possible a fast, comprehensive and detailed study of all design possibilities and assumptions. The study would not have been feasible without highly accessible automatic computation facilities since each change in an assumption or parameter requires, in effect, an iteration for a new aircraft.

The weight breakdowns for representative aircraft are given on pages II-29 to II-33.

Since these studies are intended to be predictions of potential vehicle performance in the 1970-80's, it is necessary to extrapolate the existing state-of-the-art in component design. This was done by assuming that concepts which have reached experimental demonstration status and whose feasibility has been established will reach full development status during the next 10 years. On the other hand, advances which are predicted on the basis of extrapolation of trend curves, but whose method of implementation is not at the moment too clear, have not been used other than in the parametric analyses.

An example is the use of advanced structural concepts, in particular, high strength filament composites. Typically it can be shown that by the use of boron filament re-inforced plastics, a major reduction in structural weight can be anticipated on aircraft structural components, such as wings and fuselages. Similarly, it is possible to conceive of light weight lift engines with thrust to weight ratios of the order of 30 or more if such advanced structural concepts are used in the compressor design. However, at the present time, methods for using these fibers whose diameter, of the order of 5 mills, is appreciably greater than that used in standard fiber glass technology, is still in the highly exploratory state. Furthermore, in commercial operations, such as are being considered here, the initial cost of the material may outweigh the advantages gained by reduction in structural weight and it is impossible to predict at the present time the extent to which large scale production or the development of cheaper filament production techniques and substrates would reduce these initial procurement costs.

Another example is in the use of boundary layer control to increase the maximum lift coefficient of conventional or short takeoff aircraft. Certainly the feasibility of this technique has been demonstrated and it could conceivably be an operationally suitable system by the 1980's. However, the installed weight, maintenance and reliability problems involved in using this technique are presently insufficiently well defined to permit any rational predictions based on its use. Furthermore, the questions of control and handling at the very low speeds made possible by this device are not well understood and, in fact, may require the provision of some form of reaction control.

The judgment necessary in arriving at decisions of this nature as to the assumptions to be used in the analysis are certainly open to question. Therefore, the effects of these and all other basic assumptions have been tested and are presented in the discussion and figures which follows, in order that the sensitivity of the final solution may be weighed against the validity of the assumptions used.

METHOD OF COMPUTATION AND ASSUMPTIONS

Computational Techniques

All of the programs work essentially in the same manner and will be discussed together. All require various input data, such as cruise speed, altitude, number of passengers, design range, aspect ratio, ultimate load factor, seats abreast, etc. Various subroutines are built into the programs to compute atmospheric properties, accelerations and flight profiles, fuel burned and block speed for stage lengths shorter than the design range. Fuselage sizing is derived from the number of seats abreast, number of passengers, both of which are inputs, and number of exits, which is calculated. Assuming an initial gross weight, the weight of the other aircraft components is calculated. The aircraft performance is then determined and the fuel burn weights obtained, resulting in a new estimate of the gross weight. The mean between the estimated and computed weights is then used to repeat the calculations. In the rotary wing program, the second weight is used directly.

By iterative process, a gross weight is finally found which will print out as the final gross weight if within 50 pounds of the previous iteration or 10 pounds in the case of the helicopter. This is the gross weight of the aircraft and all of the component weights are now known.

The program then prints out in addition the weight breakdown, including fuel breakdown over the flight profile, and then punches out on data cards all the necessary results to calculate the direct operating costs of the aircraft (DOC). These numbers include, for example, the gross weight, empty weight, engine power or thrust, fuel burned at intermediate ranges, and block speeds for all intermediate ranges. These data cards are fed directly into the DOC program, which calculates the DOC of the aircraft. This method of slaving one program to the output of another is a fast and efficient way to analyze all of the design variations carried out in this study, and allows various economic parameters to be varied for each design.

Assumptions Common to all Configurations

The general assumptions which apply to more than one configuration will first be reviewed.

Fundamental to all the VTOL aircraft is the requirement of a hover capability with one engine-out without sacrificing control capability. While this requirement may appear unduly conservative, it is believed that all weather operation in and out of highly populated centers from airports or landing pads located in highly congested areas could not be tolerated unless the aircraft were capable of maintaining altitude at all points in the flight path, down to and including the hover condition, with one engine out. Furthermore, the VTOL aircraft have been assumed to be operable without the need for air or ground maneuvering time, which, in effect, specifies no restriction on approach paths. For these reasons, it has been assumed that the safety feature of engine-out hover capability is mandatory in all the VTOL designs considered in this report. The STOL is provided with an interconnecting shaft and, although not capable of one engine-out takeoff in the maximum takeoff distance of 500 feet, a safe abort will be possible in the field length provided.

In the case of the jet lift aircraft, the installed thrust to weight ratio required to provide an engine-out hover capability was computed to be 1.5 which allows for the shut-down of another engine in order to maintain symmetry while leaving sufficient excess thrust to insure a control capability amounting to approximately 1/2 radian per second squared acceleration in pitch and a margin for deceleration of the aircraft. Twelve lift engines are assumed located in two engine bays in the fore and aft sections of the fuselage. Two cruise engines are assumed located in the rear whose thrust can be deflected either by exhaust vectoring or engine rotation. For the helicopter, the rotor thrust capability with one engine-out was taken as 1.1 times the gross weight. For the tilt wing aircraft which was assumed to be provided with monocyclic pitch propellers for control in pitch, differential collective for roll and ailerons for yaw, the thrust to weight ratio with one engine-out was taken as 1.15.

For all V/STOL aircraft, the engines were sized on the basis of a 90° F day and sea level takeoff. This is the critical condition for the Northeast Corridor during the summer. Cruise power for conventional and jet lift cruise engines was taken as 90% of normal rated power. Takeoff power was based on a 30-minute maximum continuous rating, taken as 1.2 times normal rated power.

The variation of jet thrust and shaft power with altitude were both approximated by the following relationship:

$$\text{Thrust or power} = (\text{Thrust or Power})_{\text{SL}} \left[1 - .55 \, \frac{\text{altitude in feet}}{30{,}000} \right]$$

The variation of power and thrust with temperature was taken to be

$$\text{Thrust or power} = (\text{Thrust or power})_{\circ}\left[1 - \frac{K\ (T_{SL} - 520)}{30}\right]$$

where the factor K was .15 for shaft engines and .08 for jet engines, and the subscript refers to standard day (520°R) conditions.

The static sea level specific fuel consumptions with the shaft turbine engine used in the tilt wing, STOL, and helicopter aircraft was taken as .55 to allow for 90° day operation. No reduction in specific fuel consumptions with altitude and speed was taken since it was assumed that the normal rated rpm of the engine would have to be considerably reduced while maintaining full cruise power in order to avoid excessive propellor tip Mach numbers and realize reasonable efficiencies. An investigation of the various advanced free turbine engine concepts indicated that the reduction in specific fuel consumption normally anticipated with altitude and speed was just about compensated by the increase in specific fuel consumption associated with the reduction in the power turbine speed.

The variation of specific fuel consumption with power was approximated where required as

$$SFC = (SFC)_{NRP} \left[\frac{\text{Normal Rated Power}}{\text{Power Used}} \right]^{.36}$$

A static sea level specific fuel consumption of the jet lift engines was taken as .7. This corresponds to engines with a bypass ratio of 2 (bypass air equal to twice primary engine air). Although this corresponds to existing state-of-the-art capabilities, it is not anticipated that the thrust specific fuel consumption of the turbo fan lift engines will be appreciably reduced since the tendency toward smaller volume and higher turbine inlet temperatures will have a reverse effect, probably resulting in no appreciable improvement in static specific fuel consumption for these engines.

The variation of specific fuel consumption with speed and altitude of the lift engines during the acceleration phase was taken as

$$TSFC = TSFC_{o} + \frac{0.12v}{200} - .1 \left[\frac{\text{Altitude}}{30{,}000} \right]$$

In the jet lift aircraft the cruise engines were assumed to be turbo fans with a thrust specific fuel consumption of .55 which varied with the speed and altitude as follows

$$TSFC = TSFC_o + 0.45\ M - .05\left[\frac{Altitude}{30,000}\right]$$

It has been assumed that no emergency rating exists on any of the engines. There appears to be no doubt that in the future such emergency rating will be authorized on turbine engines in view of experiences to date with these engines in service. This rating would permit at least a twenty percent increase in thrust and even more in power for a very short period, of the order of one or two minutes, followed by the removal of the engine before any further reuse and a complete teardown and inspection. However, at the present time, U.S. engine manufacturers do not willingly concede the feasibility of such rating and there is certainly question as to whether the lighter turbine wheels envisaged for the light weight lift engines will provide the necessary heat-sink to permit the short term over-temperature condition implied by this rating. It is obvious, however, that for VTOL aircraft, a provision of a short period emergency rating to permit engine-out hover without the necessity of installing additional engines would be of great benefit, and it is reasonably certain that this provision will eventually be made available, but only after a considerable amount of operational experience with VTOL concepts has been accumulated.

Regenerative engines have not been considered for the shaft drive applications because the additional weight in pounds of the regenerator, approximately 10 percent of the horsepower, would not justify the reduced fuel consumption for the short ranges being considered in this study, the cross-over point occuring beyond a range of 200 miles.

The thrust to weight ratio of the shaft drive engines has been taken as 7.5 based on maximum continuous power at sea level standard condition. The installation factor has been taken as 1.5 exclusive of the fuel system. Thus, the total installed weight of the powerplant is 1.5 times the dry engine weight.

The thrust to weight ratio of the lift engines has been taken as 25 and the installation factor was taken as 2. In addition, the fuselage weight was increased by the additional length required for two-engine bays which, in general, resulted in an installation factor of between 2.5 and 3. Experience with present-day installation of jet lift engines has indicated that the installation factor is actually closer to 1.5. However, this is for engines whose dry thrust to weight ratio is of the order of 15. It is certainly possible that the newer generation of light weight lift engines whose thrust to weight ratio exceeds 20 and whose volume for given thrust is approximately 1/3 of the present generation will be able to achieve installation weights not much higher than 50% of their dry weight. The engine air intake louvers or doors and exhaust system represent a large percent of the installation weight. These could be expected to decrease in weight as the engine volume decreases and thrust per pound of air increases. However, until these factors are better defined, it is believed reasonable to assume that the installation weight does not decrease as rapidly as the dry engine weight. The effect of the degree of conservatism implied by this relatively high installation factor is discussed below (page II-39).

The thrust to weight ratio of the cruise turbo fan engines was taken as 10, based on maximum thrust, excluding thrust deflectors which were included in the installation factor, again taken as 2. Projected weights for advanced cruise engines in military applications are somewhat lower; however, the high reliability of commercial cruise engine and low maintenance requirements will, it is believed, result in the optimization at the value of 10.

The remaining weight items were computed using the standard type of statistically derived weight formulae conventionally used in aircraft design predictions. The relationships developed by several aircraft manufacturers were obtained and checked against known aircraft component weights and where necessary the formulae were modified to suit the requirements of this study. As is the case of most weight data, much of the information used is of a proprietary nature. Therefore, the exact formulae used in this analysis are not always given in this report. However, the basic assumptions used will be briefly reviewed in order that the individual weight items contained in the table of representative weight breakdowns can be individually verified.

Weights are based on present-day weight trend curves with no projection into the future except as noted below. Most of the items involve structural weight items and, as mentioned previously, no major breakthrough resulting in a reduction in the weight of primary structure in the aircraft can be anticipated with the possible exception of the use of high strength filament composites.

The fuselage was assumed to be pressurized with a pressure differential of 6 pounds per square inch. Although it is not necessary to operate the aircraft at high altitudes, it was believed essential to maintain cabin pressurization of this level in order to permit rapid descents without passenger discomfort. It was assumed that each fuselage had one regular door, plus one ~~emer-~~ extra gency ~~exit~~ door per side for every forty passengers with an emergency exit opposite each door. Furnishings and equipment were assumed to weigh 400 pounds plus 50 pounds for each crew member, plus 40 pounds per passenger. This implies light weight seats, but otherwise represents a compromise between an austere interior and present-day jet accomodations, with suitable allowance for soundproofing and interior finish. Provision for air conditioning and anti-icing was 500 pounds plus 13 pounds per passenger.

As mentioned previously, fuel tanks were not included in the engine installation weights. It was assumed that fixed wing aircraft had integral fuel tanks weighing .045 lbs. per lb. of fuel capacity. This was raised to .075 per pound capacity for the rotary wing aircraft for which the fuel was assumed to be stored in separately structured tanks.

All landing gear weights were assumed to be 3% of the gross weight of the aircraft. It is possible that this weight could be reduced for the VTOL aircraft with automated landing and altitude hold systems. However, landing gear design loads for VTOL aircraft are frequently determined by ground handling requirements and not landing impact loads. Furthermore, the landing gear system represents one of the highest cost items in aircraft maintenance, frequently as high as 15% of total maintenance. Therefore, it does not seem reasonable to project ultra-light landing gear on the VTOL aircraft at the present time.

A two-man operating crew, together with one cabin attendant, were assumed. Crew and passenger weight was taken as 200 pounds per person.

No galleys and only one toilet were allowed for in weight. The high density seating of 33-inch pitch was used in determining the fuselage length. An aisle width of 20 inches and a seat width of 19.2 inches were assumed. The seating was taken to be 3,4, and 5 seats abreast for the 40,80, or 120 passenger vehicle respectively.

The weight of trapped oil was assumed to be 35 pounds per engine.

Finally, a maximum cruise lift coefficient of .5 was used in estimating wing areas in all aircraft even though maximum L/D for some of the configurations occurred at an appreciably higher lift coefficient. This limit on cruise lift coefficient was established in order to insure reasonable safety from gust induced stalls particularly for the very high wing loadings at which some of the jet lift aircraft optimized.

All aircraft were designed for an ultimate load factor of 4.5.

The relationship used for fixed wing aircraft drag based on wing area was

$$C_{D_o} = C_{D_o \text{ wings}} + C_{D_o \text{ tail}} + C_{D_o \text{ misc.}} + .1 \frac{Sf}{S_w}$$

$$\text{or} \qquad C_{D_o} = .008 + .004 + .001 + .1 \frac{Sf}{S_w}$$

where S_w is the wing area.

The tilt wing aircraft was assumed to cruise with a propeller efficiency of .8 and the STOL aircraft was assumed to cruise with a propeller efficiency of .875. On both aircraft a transmission efficiency of .9 was used.

The various assumptions which apply to specific configurations will now be separately discussed.

Jet Lift Aircraft

As discussed above (page II- 6), the jet lift aircraft had an additional fuselage length to allow for the installation of lift engines in two engine bays located in a forward section and aft sections of the fuselage. It was assumed that the lift engines had an effective loading of 1,000 lbs. per square foot over the horizontal cross-section of this engine bay. This would permit the installation of two lift engines side by side with an aisle for walking from the cockpit to the passenger compartment.

Fuel for an air restart was included if the range exceeded 30 miles. It was found, for shorter ranges, that leaving the lift engines idling resulted in less fuel consumption. An airstart was assumed to consume the same fuel as a ground start, that is, one-half minute at full thrust and one-half minute at idling. Experience with existing jet lift aircraft indicates that this assumption is somewhat conservative and, in fact, the engines could be started and accelerated as required to equilibrium thrust during the transition maneuver since the engine acceleration time is always less than the required time for aircraft deceleration. In the event of failure of any engine to develop the required thrust, the approach could be abandoned with complete safety at any point. The effect of assuming this type of approach and transition maneuver is shown in Figure II-4. The effect is particularly noticeable in the shorter stage lengths, but in general is not great.

Tilt Wing Aircraft

The tilt wing design was centered around a disc loading equal to 60 percent of the wing loading. Studies showed that increasing the disc loading increases the cost, largely due to increased hover power, and that reducing it reduces the cost. However, a minimum disc loading of approximately 50% of wing loading is required in order to maintain sufficient slip stream velocity over the wing in order to prevent stall and undesirable handling qualities in descent and reverse transition. Even this ratio requires fairly sophisticated high lift devices, both at the leading and trailing edges of the wing, to insure satisfactory control in approach and the absence of buffeting. Consequently, 60% was chosen, with a minimal overlap in order to maintain a reasonable aspect ratio for the wing.

The ratio of thrust coefficient to solidity C_T/σ , which in effect defines the mean blade lift coefficient, was set at .12 and the solidity σ was limited at .25 as being the maximum reasonable value. These limits were chosen after a study of a number of current and projected tilt wing aircraft designs. The choosing of C_T/σ effectively limits the disc loading, and, therefore, the wing loading, and sets an optimum cruise speed.

Propeller tip speed in hovering flight was limited to a Mach number of .75 from noise considerations when operating from urban centers. The power required was computed from induced power assuming uniform inflow, and from profile power using a blade profile drag coefficient of .01. This power was then increased 10% to allow for the effects of nonuniform inflow due to the compromises in twist required to achieve reasonable cruise efficiencies.

STOL Aircraft

The wing loading of this type aircraft was set at 50, corresponding to a landing capability over a 50-foot obstacle of 1,000 feet. This number was arrived at after study of current STOL aircraft operating characteristics and is based on an assumed wheel braking friction factor of $\mu = .2$, corresponding to a wet runway, and a reverse thrust capability of .25g.

Maximum lift coefficient at landing was taken as $.9C_{L_{max}}$ with a $C_{L_{max}}$ of 3.35. The effect of assuming the higher lift coefficient achievable with boundary layer control is shown in Figure II-6.

The propellers were sized by assuming that the ratio of horsepower to propeller diameter squared was 7.5. A propeller solidity of .165 was assumed. These relationships were established as a result of propeller optimization studies as being reasonably representative. Their use considerably simplified the computational process. Corresponding efficiencies were centered around 87-1/2 percent, which was used in all computations.

Propeller weights were based on the light weight propeller/ rotor technology which has been developed for tilt wing aircraft. There may be some question as to the practicability of designing STOL propellers on this basis in view of their greater proximity to the ground and, hence, greater susceptibility to pebble damage and abrasion. However, the aircraft in this study are designed to operate from prepared and carefully maintained areas; hence, this assumption is believed to be reasonable.

Helicopter

The rotor is designed for the high speed cruise condition By choosing a tapered blade with a NACA 0012 section at the root and a NACA 0006 section at the tip, a tip Mach number on the advancing blade of .95 can be used without appreciable compressibility losses. Given the design cruise advance ratio, μ , and ambient air conditions, the tip speed and the cruise speed (V) are determined.

Based on an optimization study in an unpublished reference, a cruise C_T of .005 and a rotor solidity, σ, of .075 were assumed. Given these values and if the number of blades (typically 4) and the number of rotors are chosen and the gross weight is estimated, then the rotor radius and chord can be determined.

Cruise flight performance is determined on the basis of a rotor equivalent lift to drag ratio $(L/D)_R$, an equivalent flat plate area of the fuselage and rotor hub (F), and the wing lift to drag ratio $(L/D)_W$. Reference II-1 estimates $(L/D)_R$ vs. V for both a pure helicopter and a compound with the wing carrying 75 percent of the weight and estimates the maximum allowable cruise speed due to aeroelastic rotor limits for both types of rotary winged aircraft. Using these estimates and assuming a tip Mach number limit of .95, and altitude of 1,500 feet, and a 90° hot day, the following table of L/D_R vs. μ has been generated. This table has been used for the parametric studies and for the advanced technology (1980) helicopter (Fig. I-4). For the 1970 time period helicopter (Fig. I-3), an $(L/D)_R$ of 9 has been used.

μ	.35	.40	.45	.50	.54	.575
$(L/D)_R$ helicopter	12.0	11.5	11.0			
$(L/D)_R$ compounds			13.5	13.0	12.5	12.0

The limit speed for a pure helicopter is taken to be $\mu = .45$ (200 kts.), for a compound 75% unloaded with no auxiliary propulsion $\mu = .54$ (225 kts.), and for a compound 75% unloaded with auxiliary propulsion $\mu = .575$ (235 kts.).

For use on the compound types, a wing of aspect ratio 6 and 12 percent thickness was chosen. The wing is sized for a $C_L = .5$ in cruise and has an estimated $(L/D)_W = 25$. Additional weight for auxiliary propulsion of 8% of gross weight was added as well as a wing weight corresponding to 75% unloading of the rotor.

Reference II-2 indicates that F is proportional to the gross weight (W) to the 2/3 power and estimates the constant of proportionality (CF) as .045 for current helicopters and .01 for fixed wing aircraft. A goal of .015 is mentioned for advanced helicopters. For the present study, a value of .02 has been used ($F = .02\ W^{2/3}$). A typical drag breakdown for an 80 passenger, 50,000 pound gross weight, tandem helicopter is shown to indicate how this is distributed. (See Page II-24).

An overall aircraft equivalent lift to drag ratio can now be calculated (L/D).

$$L/D = \frac{1.0}{\frac{1.0}{L/D_W} + \frac{1}{2}\rho\frac{V^2 f}{W} + \frac{L_R}{W}\left(\frac{1.0}{L/D_R} - \frac{1.0}{L/D_W}\right)}$$

where ρ = ambient air density, V = flight speed, and $\frac{L_R}{W}$ = ratio of rotor lift to gross weight ($\frac{L_R}{W}$ = 1.0 for helicopters and $\frac{L_R}{W}$ = .25 for 75% unloaded compounds).

To calculate the horsepower required the various losses due to the drive system, interference, etc., must be estimated.

The following losses have been assumed, in percent of total.

ITEM	SINGLE ROTOR	TANDEM ROTOR	AUXILIARY PROPULSION
Drive System	2	6	
Tail Rotor	10	0	
Interference	2	4	
Tip Loss	2	2	
Total Hover	16	12	16
Total Cruise	4	8	14

The allowance made for an auxiliary propulsion system where applicable, such as a swiveling tail rotor, includes transmission losses and propulsive efficiency.

For hovering a $C_T/\sigma = .1$ is used and the tip speed is found by requiring a thrust $T = 1.1W$. The horsepower required is then found conventionally assuming one engine out, $T = 1.1W$, and a 30-minute rating on the engines of 1.2 times normal rated power. This engine-out case normally sizes the engines (instead of cruise power required).

Having determined the engine size, both hover and cruise fuel flow rates can now be determined.

In the present program, both acceleration and climb use the 30-minute rating on all engines and this sizes the drive system, since hover power and cruise power at altitude were both appreciably less. An alternative would be to size the drive system for either hover or cruise, whichever requires the most power, and limit the power used for acceleration and climb. This would probably result in optimization at a smaller number of engines than the case actually used because the drive system is relatively much heavier than the engines.

A typical drag breakdown for the helicopter is compared below with the result obtained from the approximation given above.

ITEM	AREA	COEFFICIENT	F
Fuselage	2140	.0035	7.5
Aft Pylon	150	.02	3.0
Fwd Pylon	12	.25	3.0
Hubs	13	.25	3.2
Blade Shanks & Interference			3.5
Hub-Pylon Interference			1.0
Nacelles	15	.20	3.0
Sub-total			24.2
Roughness (5%)			1.2
Protuberances (5%)			1.2
Leakage (2%)			.5
Cooling			.5
Total			27.6

For Comparison,

$$F = .02\ W^{2/3} = .02\ (50{,}000)^{2/3} = 27.2$$

In addition to the compound and conventional helicopter, a stowed rotor configuration was examined. In this aircraft the rotor is stopped at transition speed and stowed to reduce drag in the upper portion of the fuselage. The aircraft then operates as a conventional jet aircraft. It was assumed that the rotor and drive system weight was 20% of the gross weight. Convertible engines, with the power section used for both cruise as a bypass jet and to drive the rotor in hover with a thrust to weight ratio of 10 were assumed. Because of the necessary compromise, the specific fuel consumption was taken as .9 pounds per horsepower per hour. The rotor was assumed to have a thrust to power ratio of 10 pounds per horsepower.

An average acceleration to cruise speed of .1g to allow for conversion and stowing and a deceleration of .125g were used. The fuselage frontal area was increased 50% to allow for rotor stowage and the drag formula of page II-16 was then applied.

Conventional Short Range Aircraft

The direct operating cost of a short haul aircraft typical of present-day technology was computed. Comparing the answers obtained from the test program with the data available, it was found that the assumptions and equations used accurately predicted actual present-day aircraft weights and DOC's.

A new short haul transport was then designed using the same predicted furnishings cost formula and engine thrust to weight ratio, as were being used in the studies of the VTOL and STOL aircraft. The test program was then rerun, the results being used in the DOC program. The DOC results are summarized in graphs II-76 to II-78.

Flight Profiles

The flight profile used for the VTOL aircraft includes:

1. No ground or air maneuver time.
2. Vertical climb to 50 feet.
3. Horizontal acceleration of .5 g if possible to climb speed.
4. Climb at maximum rate of climb.
5. Cruise at maximum cruise speed.
6. Descent at cruise speed, idling engines.
7. Deceleration of .25 g to 50 feet altitude.
8. Land.
9. Fuel allowances in addition to above: 20 minutes reserve according to CAR 46.396 for domestic helicopters and 1/2 minute at full thrust, all engines, and 1/2 minute at idle.

The flight profile for the STOL aircraft is as follows:

1. 6 minutes at idle, includes taxi in and out.
2. Maximum takeoff power to climb speed.
3. Climb at maximum rate of climb.
4. Cruise at cruise velocity per schedule.
5. Descend at cruise speed, engines idling.
6. 4 minutes of air maneuver time in landing configuration and cruise fuel consumption.
7. Landing.
8. Reserves are 30 minutes at cruise fuel consumption.

The flight profile for the conventional aircraft is as follows:

1. 10 minutes of idle, taxi in and out.
2. Maximum takeoff power to climb speed.
3. Climb at maximum rate of climb.
4. Cruise at cruise velocity at 30,000 feet altitude.
5. Descend as above.
6. 5 minutes of air maneuver.
7. Landing.
8. Reserves:
    a. enough fuel to provide additional cruising for 10% of flight time, divert to the alternate 230 statute miles distant and hold at 1,500 feet for 1/2 hour., or
    b. 10,000 pounds.

For the advanced short haul conventional aircraft the reserves were taken as 30 minutes at cruise power, as for the STOL aircraft. Cruise altitude was limited to 27,000 feet.

CHARACTERISTICS OF TILT WING AIRCRAFT

80 Passenger - Design Range 200 Miles

Cruise Altitude 20,000 ft.
Cruise Speed 400 mph

Structure	Weight (lbs.)
Wing	6,279
Fuel Tanks	174
Flight Control	1,185
Tail	1,185
Fuselage	8,266
Landing Gear	1,777
Propulsion System	12,337
Navigation Instruments	200
Hydraulics	643
Electrical Equipment	678
Electronics	642
Furnishings	3,750
Air Conditioning & de-icing Equipment	1,540
Weight Empty	38,611
Payload & Crew	16,600
Trapped Oil	140
Fuel	3,895
Gross Weight	59,246

Aircraft Characteristics

Wing:
Span = 82.15
Aspect Ratio = 9.5
Area = 710 sq. ft.
Wing Loading = 83.40 psf.
Taper Ratio = .5

Fuselage:
Length = 94.8 ft.
Diam. = 8.72 ft.
Seats abreast = 4

Engines = 4 at 6,880 HP
30 minute rating

Propellers:
Disc Loading = 50.04 psf.
Diameter = 19.4 ft.
Solidity = .25
4 propellers

Fuel Breakdown:

	Fuel (lbs.)	Range (mi.)
Hover & Warm-up	138	--
Acceleration & Climb	643	14
Cruise	1,430	133
Descent & Deceleration	261	53
Reserves	1,423	--
Total	3,895	200

CHARACTERISTICS OF JET-LIFT AIRCRAFT

80 Passenger - Design Range 200 Miles

Cruise Altitude 20,000 ft.

Cruise Speed 450 mph

Structure	Weight (lbs.)
Wing	3,828
Fuel Tanks	231
Flight Control	1,211
Fuselage	10,380
Tail	1,138
Landing Gear	1,707
Propulsion System	8,758
Navigation Instruments	200
Hydraulics	610
Electrical Equipment	664
Electronics	642
Furnishings	3,750
Air Conditioning & De-icing Equip.	1,540
Weight Empty	34,658
Payload & Crew	16,600
Trapped Oil	490
Fuel	5,154
Gross Weight	56,902

Aircraft Characteristics

Wing:
Span = 50.3 ft.
Area = 421 sq. ft.
Wing Loading = 135 psf.
Taper Ratio = .5

Fuselage:
Length = 112.1 ft.
Diameter = 8.72 ft.
Seats abreast - 4

Engines:
Cruise 2 at 6,030 lb.thrust 30-minute rating
Lift 12 at 7,360 lb.thrust 30-minute rating

Fuel Breakdown:

	Fuel(lbs.)	Range(mi.)
Hover & Warm-up	637	--
Acc.&Climb	1,107	30
Cruise	1,060	124
Restart	471	--
Descend & Decelerate	604	46
Reserves	1,275	--
Total	5,154	200

CHARACTERISTICS OF CONVENTIONAL HELICOPTER

80 Passengers - Design Range 200 Miles

Cruise Altitude 1,500 feet

Cruise Speed 212 mph

Structure	Weight(lbs)
Rotor	9840
Drive System	7623
Flight Controls	1548
Fuselage	7334
Undercarriage	1849
Installed Engines	2395
Navigation Instruments	200
Hydraulics	679
Electrical Equipment	692
Electronics	642
Furnishings	3750
Air Conditioning	1540
Fuel System	477
Weight Empty	36441
Payload & Crew	16600
Trapped Oil	105
Fuel	6364
Gross Weight	61,638

Aircraft Characteristics

Rotors (2):
Solidity = .075
Area = 9,508 sq. ft.
Radius = 39 ft.
Tip Speed = 776 ft/sec.

Fuselage: 77
Length = ~~68~~ ft.
Diameter = 8.72 ft.
Seats abreast = 4

Engines:
3 at 4,025 HP
30 minute rating
90° F.S.L.

Fuel Breakdown:

	Fuel(lbs.)	Range(mi)
Hover & Transition	70	2.6
Climb	42	0.8
Cruise	4,552	195.0
Descent	8	1.6
Reserves	1,692	---
Total	6,364	200.00

CHARACTERISTICS OF STOL AIRCRAFT

80 Passengers - Design Range 200 Miles

Cruise Altitude 15,000 ft.

Cruise Speed 350 mph

Structure	Weight(lbs.)
Wing	6,553
Fuel Tanks	168
Flight Control	1,051
Fuselage	8,120
Tail	1,577
Landing Gear	1,577
Propulsion System	5,834
Navigation Instruments	200
Hydraulics	552
Electrical Equipment	636
Electronics	642
Furnishings	3,750
Air Conditioning & De-Icing Equip.	1,540
Weight Empty	32,077
Payload & Crew	16,600
Trapped Oil	140
Fuel	3,756
Gross Weight	52,573

Aircraft Characteristics

Wing:
Span = 85.8 ft.
Aspect Ratio = 7
Area = 1,051 sq. ft.
Wing Loading = 50 psf
Taper Ratio = .5

Fuselage:
Length = 94.8 ft.
Diameter = 8.72 ft.
Seats Abreast = 4

Engines:
4 at 2,444 HP
30-minute rating

Propellers:
Diameters = 16.5 ft.
Solidity = .165

Fuel Breakdown:

	Fuel(lbs)	Range(mi)
Taxi	76	--
T/O & Acc.	129	7
Climb	359	15
Cruise	1,255	145
Descend & Decelerate	98	33
Maneuver	321	--
Reserves	1,518	
Total	3,756	200

CHARACTERISTICS OF 1980 CONVENTIONAL SHORT HAUL AIRCRAFT

80 Passengers - Design Range 200 Miles

Cruise Altitude 27,000 ft.

Cruise Speed 430 mph

Structure	Weight(lbs)
Wing & Fuel Tanks	4,972
Flight Controls	898
Tail	1,418
Fuselage	8,379
Undercarriage	2,127
Installed Engines	1,572
Navigation Instruments	200
Hydraulics	481
Electrical Equipment	945
Electronics	642
Furnishings	3,750
Air Conditioning & De-icing Equip.	1,540
Weight Empty	26,924
Payload & Crew	16,600
Trapped oil	150
Fuel	3,146
Gross Weight	47,020

Aircraft Characteristics

Wings:
Span 62.1 ft.
Area = 536 sq. ft.
Aspect Ratio = 7.2
Wing Loading = 78.54 psf
Taper Ratio = .372

Fuselage:
Length = 95.12 ft.
Diameter = 10.32 ft.
Seats abreast = 5

Engines:
3
Thrust of 1 eng. = 3939

Fuel Breakdown:

	Fuel(lbs)	Range(mi)
Idle	45	--
Approach	361	--
Acceleration	153	4
Climb	1,029	73
Cruise	175	28
Descent	233	91
Deceleration	29	4
Reserves	1,121	--
TOTAL	3,146	200

DISCUSSION OF RESULTS

Optimization Studies of VTOL and STOL Aircraft

The first investigations to be performed included studies of optimum flight conditions for each of the three fixed wing VTOL and STOL aircraft. Since earlier computer programs were used for some of the optimization and parametric studies, the results will not always correspond in absolute value. However, the relative values and trends are not affected by the changes and, hence, these studies were not rerun.

The variations of DOC with altitude for all aircraft were small; hence, the choice of altitude would be dictated by passenger comfort. The schedule of cruise altitude as a function of range for all aircraft was 2,500 ft. for stage lengths less than 30 miles, 6,000 ft. for stage lengths less than 60 miles, 15,000 ft. for stage lengths less than 100 and design altitude beyond.

For the jet lift a datum of 450 mph and 20,000 ft. cruising altitude was selected (Figure II-1).

On the tilt wing, it was found that propeller efficiency falls rapidly at speeds much above 400 mph. An optimization of cruise velocity and altitude gives the results shown in Figure II-2. Because of the uncertain effects of operating a propeller/rotor at speeds involving large compressibility effects on the blade tips, a cruise speed of 400 mph at 20,000 feet was chosen as the limit for the tilt wing aircraft.

The optimization of the STOL aircraft on the basis of DOC (Figure II-3) involves a complex interplay of several parameters. The wing loading and power loading having been established by the landing and takeoff requirements, the cruise condition is, in effect, an off-design condition. Because of the relatively low wing loading required for the landing distance, established as 1,000 feet in order to ease the cost of land acquisition in metropolitan terminal areas, optimum cruise tends to occur at the higher altitudes and indeed fuel burned and gross weight were still decreasing at 25,000 feet. However, over the relatively short stage length of 200 miles used in this optimization study, the decrease in block speed due to the time required to climb to the higher altitudes tended to offset the reduction in gross weight, with the result that a minimum DOC with altitude at the higher speeds occurred around 15,000 ft. cruise altitude. The minimum with respect to speed occurs around 300 mph cruise speed since the higher cruise speeds are not compatible with optimum L/D and, hence, minimum fuel burned and minimum gross weight for the wing loadings in question, although the increase in block speed works in the opposite direction to decrease the DOC.

The third factor then enters the optimization since the lower installed powers required for speeds below 350 mph increased the ground run during takeoff beyond the 500 feet required for the specified takeoff distance. A cruise speed of 350 mph and a cruise altitude of 15,000 ft. were, therefore, selected for the datum STOL aircraft.

With the above optimization established for each aircraft, the programs were then run with these specified altitudes and cruise velocities. The relative DOC's for 80 passenger, 200-mile design range for the three aircraft can be seen on Figure II-7, and the DOC for each aircraft varying number of passengers and design range can be seen on Figures II-8,9, and 10. It was found for all aircraft that the number of passengers beyond 80 made relatively little difference. That is to say, there is great advantage in going from a 40 passenger machine to an 80 passenger machine, but relatively little advantage in going from 80 to 120 passengers. Similarly, the design stage length makes relatively little difference at the short stages being considered in this study.

The DOC of the three 80 passenger, 200-mile machines may be compared on Figure II-7. It was found that the tilt wing had a lower DOC on short ranges than the jet lift and STOL, but a higher cost on long ranges, the crossover occuring at about 100 miles. This is due to the higher fuel consumption of the jet in starting and restarting engines and during the lift off and acceleration (see page II-17 and Figure II-4). Indeed the major difference in cost at short ranges is fuel. However, the jet lift vehicle's lower gross weight and better maintenance costs (due to lack of propellers and other high maintenance items) results in a better DOC than the tilt wing at the longer ranges. The STOL DOC is higher than both, below 100 mile stage lengths, due to its much lower block speed resulting from the air and ground maneuver time required for an aircraft which must align with a runway and taxi to the unloading ramp. The effect of reducing air and ground maneuver time is shown in Figure II-5, and evidently, a serious effort to automate the STOL approach maneuvers and accelerate ground taxi would have a major beneficial effect on the operating costs.

Although many sizes of aircraft were designed, most of the results were obtained for a datum aircraft. This machine was to hold 80 passengers and fly 200 statute miles with appropriate reserves.

The general conclusion from a study of the comparative DOC of the various aircraft is that DOC cannot be taken as the primary measure of effectiveness since in fact the variations are small particularly in comparison with the indirect costs as discussed elsewhere in this report. Choice of configuration must, therefore, be based on the desired operating characteristics and mission requirements. This conclusion would not be applicable over the longer ranges, but for the very short haul aircraft considered in this study, over emphasis on the familiar DOC comparison would present a distorted view of the overall system effectiveness.

Parametric Studies for VTOL and STOL Aircraft

Parametric studies have been conducted on all the vehicles considered in this report. As in the case of the optimization studies (Page II-35), the absolute values may vary between parametric variations because of the updating of computer programs between runs; however, the relative values are consistent throughout. Each of the parameters is separately varied about a basic, datum aircraft. This datum is indicated in each of the curves that follow by the heavier line and corresponds to the assumptions listed in some detail above. By this means, the degree to which each assumption influences the final result can be readily determined. It should be reemphasized that the selected datum is not presented as a recommended configuration, but simply as a convenient basis from which to evaluate the effect of perturbations in the variables of the system. If the system of equations used to compute DOC were linear, then the effects of several changes in the parameters could be obtained by superposition. Since the system is not in general linear some error will be involved if the effects of several changes are added, but providing the effects of each individual change is not large, the error will be small.

The sensitivity of DOC to payload and design range can be seen from Figures II-8, 9, and 10. It can be seen that beyond an 80 passenger payload, there is not much reduction in DOC for a payload increase. Also, the design range does not affect the DOC to any great extent. The maximum nonstop stage length in the Northeast Corridor is 400 miles, although the average is closer to 100 miles. Because of the very low frequency of the longer hauls (Figure IV-3), it is possible that there will be only limited need for the extra range, beyond the 200 assumed as the datum. However, since the penalty in any case is small, at least the provision for greater range would probably be desirable to reduce refueling requirements.

Figures II-11 and 12 show the effect of varying propeller efficiency.

Changes in the engine installation factor (Figures II-13, 14, and 15) were found to produce more of a change in DOC for the jet and tilt wing aircraft than on the STOL. On the STOL, this factor is of relatively minor importance, but on the tilt wing and jet aircraft, it produces more significant changes, due to the high installed power.

The structural weight factor produced large changes in DOC for all aircraft, as shown in Figures II-16, 17 and 18. Light weight structures, such as might be realized with boron fiber technology, will produce substantial changes in DOC, providing the initial cost of the airframe is not appreciably increased. Estimates are that the increases in cost due to the high cost of the tungsten substrate could be offset to some extent by reduced labor costs and, in fact, a cost reduction may be realized. If less expensive substrates in the vapor deposition process of boron fiber manufacture are found practical, then the development of this structural concept would appear well worthwhile. Weight savings of the order of 30% (structural weight factor of .70) have been predicted using this technology.

Changes in transmission weight factor (Figures II-19, 20) produced fairly significant DOC changes in the tilt wing aircraft, and as might be expected, smaller changes in the STOL aircraft. Propeller weight factors (Figures II-30, 31) were also found to be of about the same significance in the tilt wing and STOL aircraft.

The thrust/weight ratio of lift and cruise engines was found to be an important parameter in the jet aircraft (Figures II-21 and 22.) Each produces a substantial change in DOC with its variations, the thrust/weight ratio of the lift engine being more significant due to the larger installed thrust of the lift engines than the cruise engines. Figures II-23 and 24 show that the horsepower/weight variation on the tilt wing and STOL aircraft produced a greater variation in the tilt wing aircraft, due to its greater installed power.

The thrust margin on the jet lift is seen in Figure II-25 to be a significant parameter, producing a decrease in DOC with its reduction. This is the penalty paid for an engine-out hover capability.

Changes in specific fuel consumption for all aircraft did not produce as much change in DOC as some of the other parameters varied.

The DOC was found to be slightly more sensitive to cruise engine TSFC variations than to lift engine specific variations. The variation of DOC to SFC variations for the propeller aircraft are shown on Figures II-26, 27. The corresponding curves for the jet are Figures II-28,29.

The maintenance factor (Maintenance Cost = M.F.xATA Modified Maintenance Cost) was found to produce great changes in DOC with its variation (Figures II-32,33 and 34). Standard maintenance factors of 1.0,1.1,1.3 were used for the jet, STOL, and tilt wing aircraft respectively (see Part III).

Utilization was found to be an important parameter on all aircraft. It was also found that there is a diminishing return on DOC for increases in utilization as shown in Figures II-35,36 and 37.

Depreciation period was found to be only mildly sensitive on all aircraft (Figures II-38, 39 and 40).

Production run (Figures II-41, 42 and 43) was found to be relatively sensitive, and it was also found that there is a diminishing returns effect on DOC for the parameter.

The engine cost in dollars per pound (Figures II-44,45 and 46) was found to be fairly important on the jet and tilt wing aircraft, but less sensitive on the STOL aircraft, due to its lesser engine weight.

Engine TBO was found not to be very sensitive and showed some effects of diminishing returns with increased TBO (Figures II-47, 48 and 49).

The usual assumption of 200 pounds per passenger and crew including baggage may be heavy for a short haul operation since fewer passengers could be expected to carry bags. Therefore the DOC was also calculated for 180 and 160 pounds per passenger. Figures II-50, 51, and 52 show the sensitivity of this parameter.

The effect of increasing the time between overhaul of the lift engines is shown in Figure II-53. It has been assumed that the TBO of the lift engines was one tenth that of the cruise engines because of their greater number of heat cycles over the operating time. It is possible that the light weight of these engines may be achievable without any sacrifice in overhaul period. Figure II-53 shows that this is not a factor of major importance in establishing the operating costs.

Advanced Technology VTOL and STOL Aircraft

The parametric studies summarized in Figures II-8 to 53 have indicated the degree of sensitivity of the direct operating costs to the assumptions used in the analysis. The reasons for selecting the datum values has been discussed in some detail above, however, their selection is certainly a matter of judgment and inevitably subjective. In general, it is believed that the results derived for the datum aircraft are those which may be reasonably anticipated in the earlier part of the next decade. Progress in aircraft design has been spectacular during the past decade and the datum solution is therefore indicative of minimal rather than maximum performance and cost capabilities.

In order to indicate the degree of improvement which can reasonably be expected during the late 1970's and early 1980's a careful review of all assumptions has been made and an "advanced technology" concept derived. The potential performance of this system is shown in Figures II-54 to 56 compared with the normal, or datum, case. Clearly, continued technological development along paths already well defined will result in major improvements in the economics of air transportation, similar to those which have been experienced during the last decade.

The basis for the advanced technology predictions may be briefly summarized as follows, using the order in which the parametric studies were discussed above.

Because of the relative insensitivity of the DOC to range and capacity beyond 80 passengers and since this size is compatible with both the estimated demand and the requirement for relatively high frequency of service, no change was made in the assumption of 200 mile design range and 80 passenger capacity.

No major improvements in propeller efficiencies, other than the unlikely use of variable diameter propellers, are forseen and hence the datum was left unchanged.

Forseeable reductions in engine installation factor are small and would have relatively little effect on the DOC. This factor was therefore left unchanged.

The structural weight factor is an important one and, as discussed previously, effective research and development is being conducted which could reduce the airframe weights by 30%. A similar reduction would occur on propellers and rotors. Work on mechanical gear drives will reduce transmission weights a proportional amount.

The landing gear weights have been reduced on all aircraft by 50%, in line with the weights of high performance aircraft, since no landings are anticipated other than on prepared surfaces and ground handling will be minimal. This reduction is particularly applicable to the VTOL aircraft. The landing gear weights were retained at the higher level for the datum aircraft because analysis of landing gear maintenance costs and experience with military aircraft have indicated that this unit is a major source of maintenance manhours. Much more work will therefore have to be done before an appreciable amount of weight can be removed from the existing wheels and struts although the landing characteristics of the aircraft and the minimal braking requirements should permit the eventual development of light weight landing gear systems by 1980.

The weights of furnishings and of seats has also been reduced to 30 pounds, typical of present day helicopter airliners, on the assumption that passengers would tolerate more austere accomodations for the short trip times envisaged for this system.

It may be assumed that the spectacular increases in engine thrust or horsepower to weight ratio of the last decade will continue through the next and that considerably lighter engines than those available in 1970 will be in service towards the 1980 period without any sacrifice in TBO. The thrust to weight ratios of the lift engines have therefore been raised to 30, of the cruise jets to 14 and of the shaft drive engines to 10. It may also be assumed that these engines will have an emergency two minute rating permitting operation at 20% over thrust or over power as previously discussed (page II-10).

Because of the need for maintaining efficient cruise and hover specific fuel consumptions (page II-8), no spectacular improvements in SFC are predicted for the shaft engines. The SFC has therefore been reduced only 10%. No change is envisaged for the jet engines, particularly the lift engines, because of the greater importance of reduced engine weight, which would always direct the compromise for the short haul vehicle being considered in this study to weight rather than reduced SFC.

The potential reduction in maintenance costs have been discussed in some detail on pages III-46 to 55 and the factor of .7 times the datum value substantiated for a fully developed and corrected aircraft. Such an evolution may be reasonably anticipated over the time period in question, assuming no major breakthrough in technology which would make re-equipment and fleet replacement desirable.

Similarly, as the use of short haul aircraft throughout the country and abroad develops, the production run could be expected to increase, consequently a run of 1,000 has been assumed.

Engine costs will also decrease and probably eventually reach the $100 per pound of the present generation (See Page III-34).

Engine TBO's are predicted to reach 10,000 hours (compared to 6,000 hours for present jet transports) with sufficient development and service experience. However, it is expected that the lift engines will continue to show appreciably shorter TBO's, and the ratio has therefore been retained at 10.

Finally, as operational experience increases, it may be expected that utilization will increase to 4,000 hours per year, either due to more efficient scheduling and management technique or by diversification to cargo as well as passenger carrying during off peak hours.

The total effect of all these advanced technology and operating concepts is summarized in Figures II-54 to 56 and these figures clearly indicate the gains which may be anticipated by continuing the intensive engineering development, largely supported by military technology, from which aircraft design has benefited in the past.

In Figures 54a to 56a only those advances directly associated with the aircraft design factors are considered. In Figures 54b to 56b those additional advances associated more with the operational rather than with the design characteristics, that is maintenance, increased utilization, increased production run and decreased engine procurement costs, are included.

Optimization and Parametric Studies of Rotary Wing Aircraft

Figure II-57 compares the various rotary wing aircraft including a stowed rotor machine. The helicopter used is the one designed for a 212 m.p.h. cruise speed, which is optimum, (Figure II-60). All these aircraft are 80 passenger, 200 mile design range machines.

As can be seen from Figure II-57 the higher gross weight of the compound types as compared to the helicopter more than offsets their advantage in block speed. In the case of the stowed rotor aircraft its high gross weight and high fuel consumption in hover as well as its relatively slow and complicated transition maneuver result in high DOC's on short stage lengths. However at longer stage lengths its very high cruise speed (450 m.p.h.) results in better DOC's than the helicopter.

The parametric variations are shown as before in a series of figures which plot DOC vs. stage length for various values of the parameter being varied. The basic case or datum about which all the variations have been made is shown as a heavy line. This basic case has a cruise speed of 230 m.p.h. which, as Figure II-60 shows, is slightly higher than the optimum. This figure of 230 m.p.h. was chosen for the datum prior to completing the optimization studies and has not been changed since the effects of cruise speed are relatively small.

The variation with number of passengers (Figure II-58) shows as before that a machine of at least 80 passengers payload is very desirable but beyond that the gain from using a larger machine is much less.

The variation with design range (Figure II-59) shows that due to the relatively low fuel consumption in hover and high fuel consumption in cruise, the helicopter is more sensitive to design range than are the fixed wing VTOL's. The design range should be chosen with care in this case to avoid the large penalties involved in designing for unnecessarily long range. The maximum stage length in the Northeast Corridor is 400 miles. However, it is unlikely that the helicopter will perform this trip and consequently the 200 mile range has been selected as the datum value.

The variation with advance ratio (cruise speed, Figure II-60) shows that a lower advance ratio allows a higher tip speed for the same maximum tip Mach number which results in both a smaller and lighter rotor and a lighter transmission. A better rotor equivalent lift to drag ratio is also possible at lower advance ratio. A trade-off between these effects and block speed results in an optimum advance ratio or cruise speed of approximately $\mu = .4$ or 212 m.p.h. for the helicopter. For the advanced technology helicopter discussed on page II-48 the optimum is even slower at approximately $\mu = .35$ or 192 m.p.h. Both compound types optimize at their maximum speeds.

The variation with cruise altitude (Figure II-61) shows that all of the rotary wing aircraft optimize at the lowest possible altitude (1,500 feet has been taken as reasonable from noise considerations) due to the penalty in block speed involved in climbing and despite the better lift to drag (L/D) ratio possible at higher altitudes.

Variations with hover altitude and sea level temperature (Figure II-62) show that a machine designed for other than sea level operation (for example the 6,000 foot and 90° F of Denver) pays a heavy penalty.

Parasite drag (Figure II-63) is clearly an important factor in determining DOC. The equivalent flat plate area due to parasite drag (including the rotor hubs), F, is determined from the relation given on Page II-20 where CF is the constant of proportionality.

The maximum tip Mach number (Figure II-64) is defined as the highest Mach number for which compressibility effects do not have to be allowed for and the rotor tip speed in cruise is determined from this tip Mach number limitation. Its effect is shown in Figure II-64 to be negligible.

The variations with engine SFC and weight per horsepower (Figures II-65 and II-66) show the effects of advanced engine technology.

The variations with rotor and drive system and structural weight factors are shown in Figures II-67 and 68. These weight factors multiply the weight trends based on current aircraft to give some estimate of the effects of advanced technology in these areas.

The variation with maintenance factor (Figure II-69) which multiplies the modified ATA maintenance cost formulae, shows the large effects of improved maintainability and reliability.

As before the DOC proved to be relatively insensitive to engine time between overhauls (TBO)(Figure II-70).

Variations with production run, engine cost, utilization and depreciation period (Figures II-71 to 74) showed the same trends as for the VTOL and STOL aircraft.

As in the case of the tilt wing and STOL aircraft, an advanced technology helicopter was defined using the same concepts as were discussed on pages II-43 to II-47. Again, the important effect of advanced technology on the costs is emphasized by the comparisons shown in Figure II-75a in which the design factors only are taken into consideration, and Figure II-75b in with both the design and operational improvements which may be anticipated at the end of the 1970-80 period are included.

Conventional Short Haul Aircraft

No parametric studies were run on the conventional short or medium haul aircraft. The DOC of a typical aircraft used at present for a medium haul operation has been computed and is shown in Figure II-76.

Conventional aircraft designed on the same basis as was used for computing the datum VTOL and STOL aircraft are shown on Figure II-77 for various passenger loads. Essentially the difference between the medium and long haul aircraft are reflected in lower DOC at the shorter ranges.

Finally an advanced short haul conventional aircraft is shown in Figures II-78a and II-78b, reflecting the effects of improved technology previously discussed (pages II-43 to II-47).

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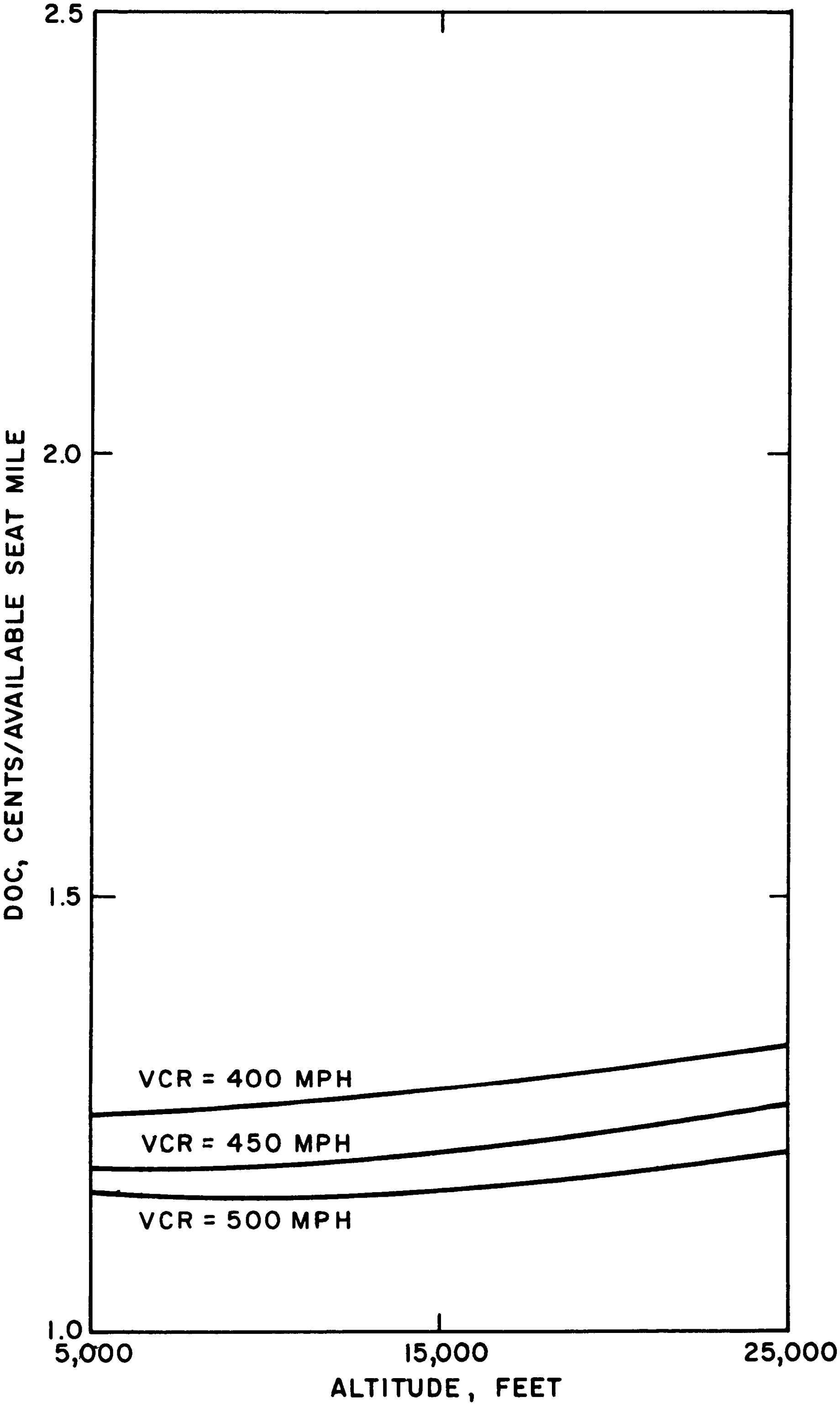

Figure II-1. JET LIFT
ALTITUDE AND CRUISE SPEED OPTIMIZATION
200 MILE DESIGN RANGE, 80 PASS.

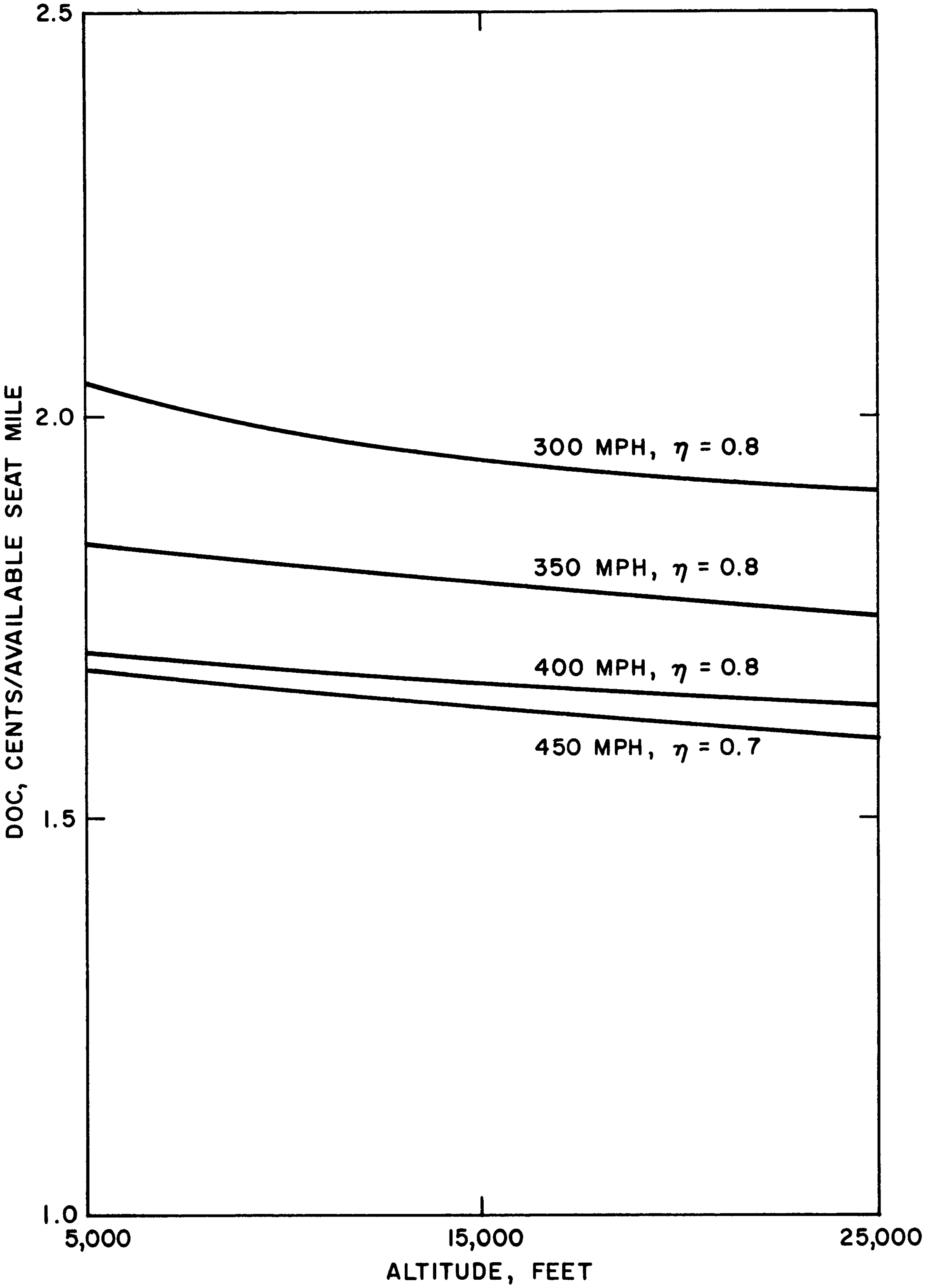

Figure II-2 TILT WING
ALTITUDE AND CRUISE VELOCITY OPTIMIZATION
200 MILE DESIGN RANGE, 80 PASS.
DISC LOADING = 60% WING LOADING

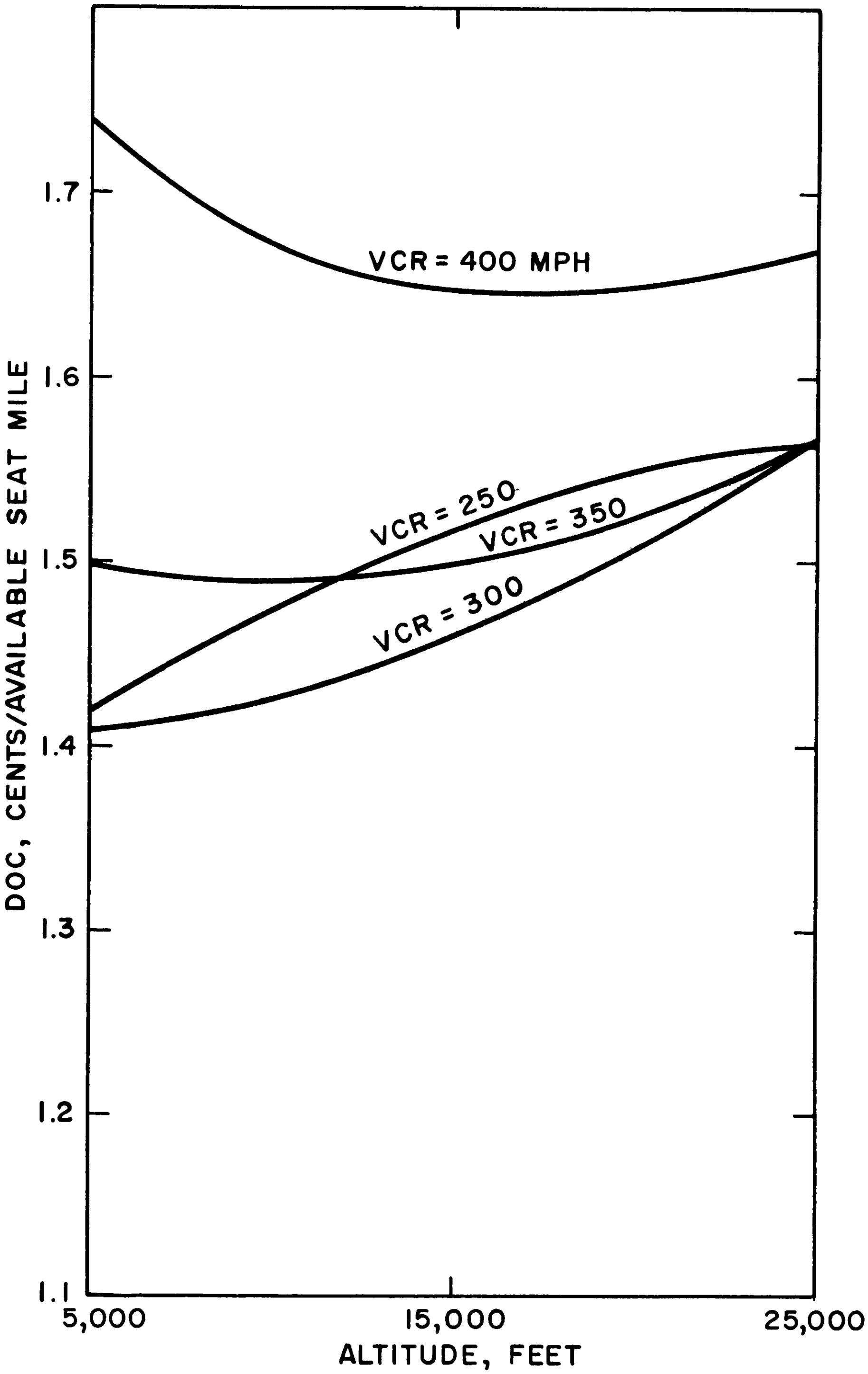

Figure II-3 STOL
ALTITUDE AND CRUISE SPEED OPTIMIZATION
200 MILE DESIGN RANGE, 80 PASSENGER AIRCRAFT

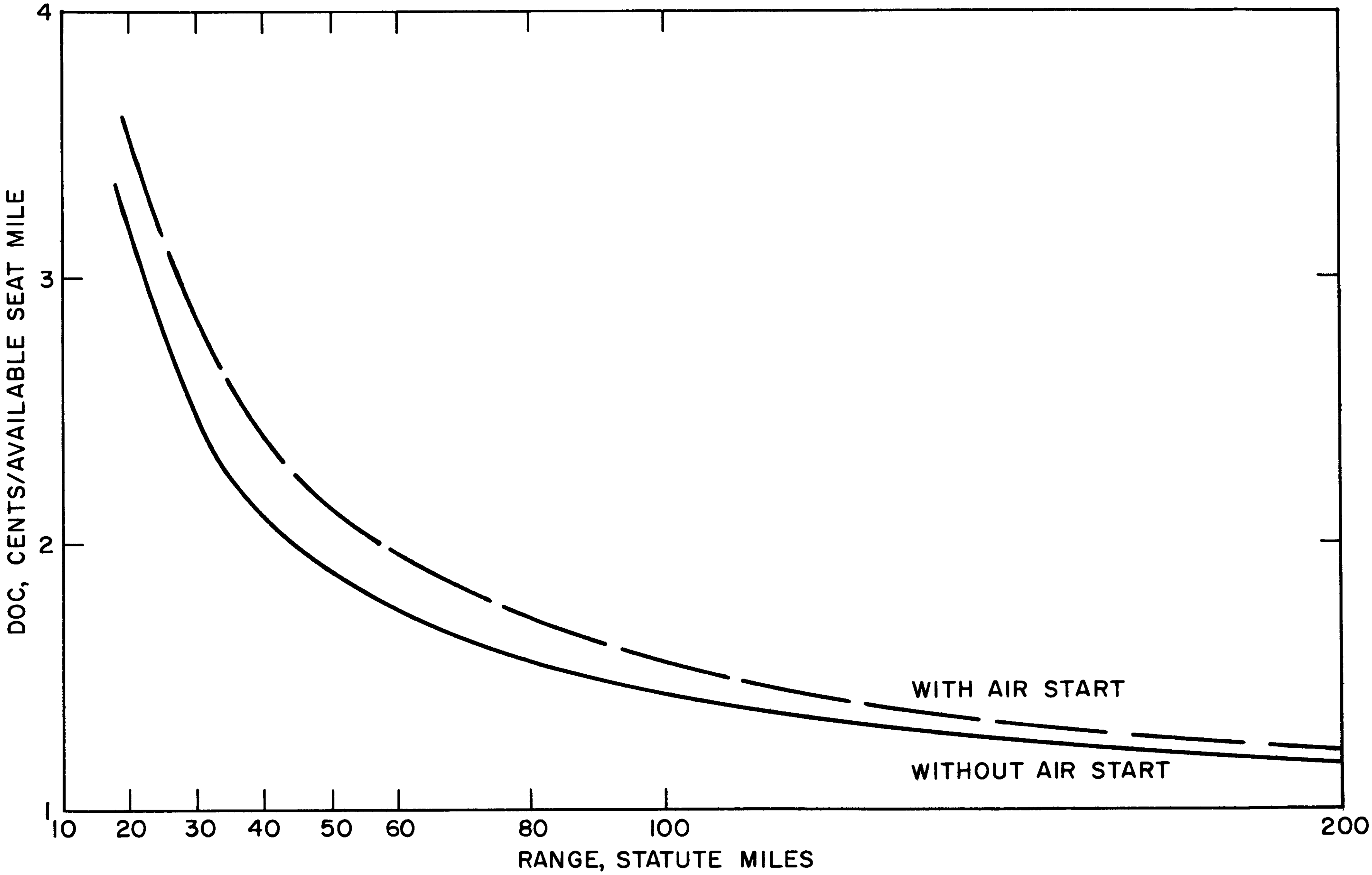

Figure II-4. EFFECT OF AIR START ON JET LIFT
200 MILE DESIGN RANGE, 80 PASSENGER AIRCRAFT
450 MPH CRUISE SPEED

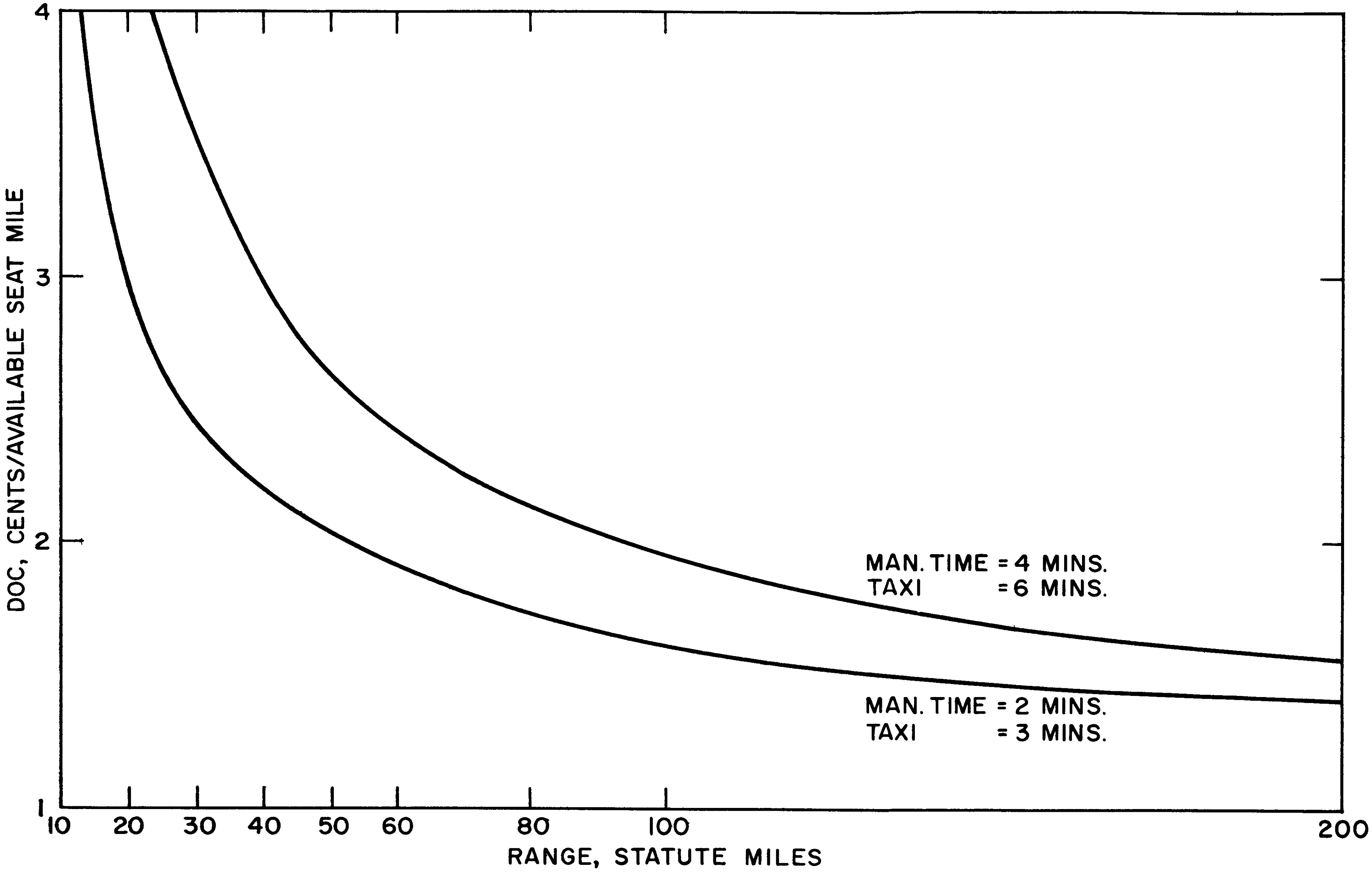

Figure II-5 EFFECT OF REDUCING AIR MANEUVER AND TAXI TIME ON STOL AIRCRAFT
200 MILE DESIGN RANGE, 80 PASSENGER AIRCRAFT

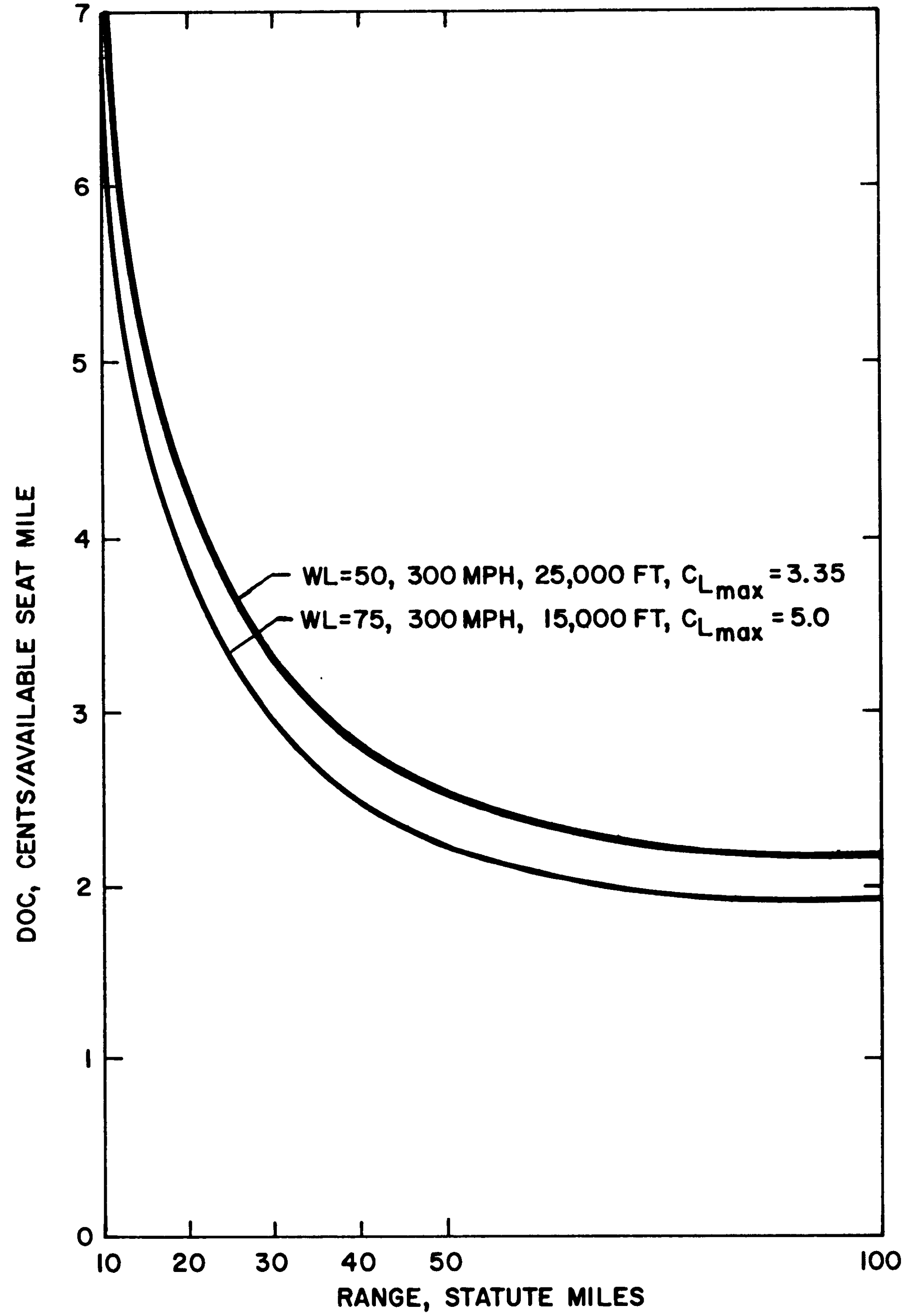

Figure II-6. STOL
VARIATION OF C_L MAX AND WING LOADING
200 MILE DESIGN RANGE, 80 PASSENGER AIRCRAFT

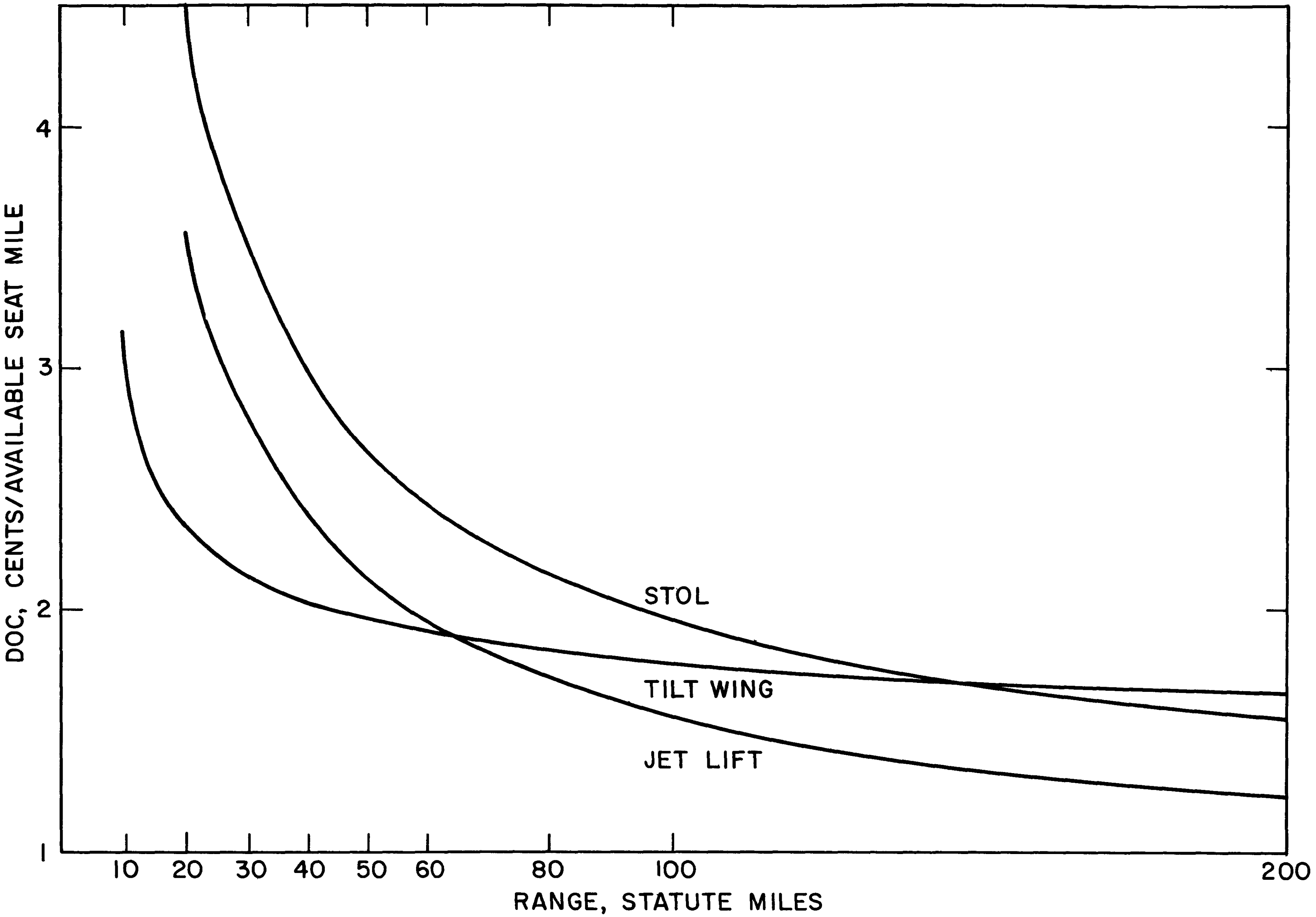

Figure II-7. COMPARATIVE AIRCRAFT
80 PASSENGER, 200 MILE DESIGN RANGE VEHICLES

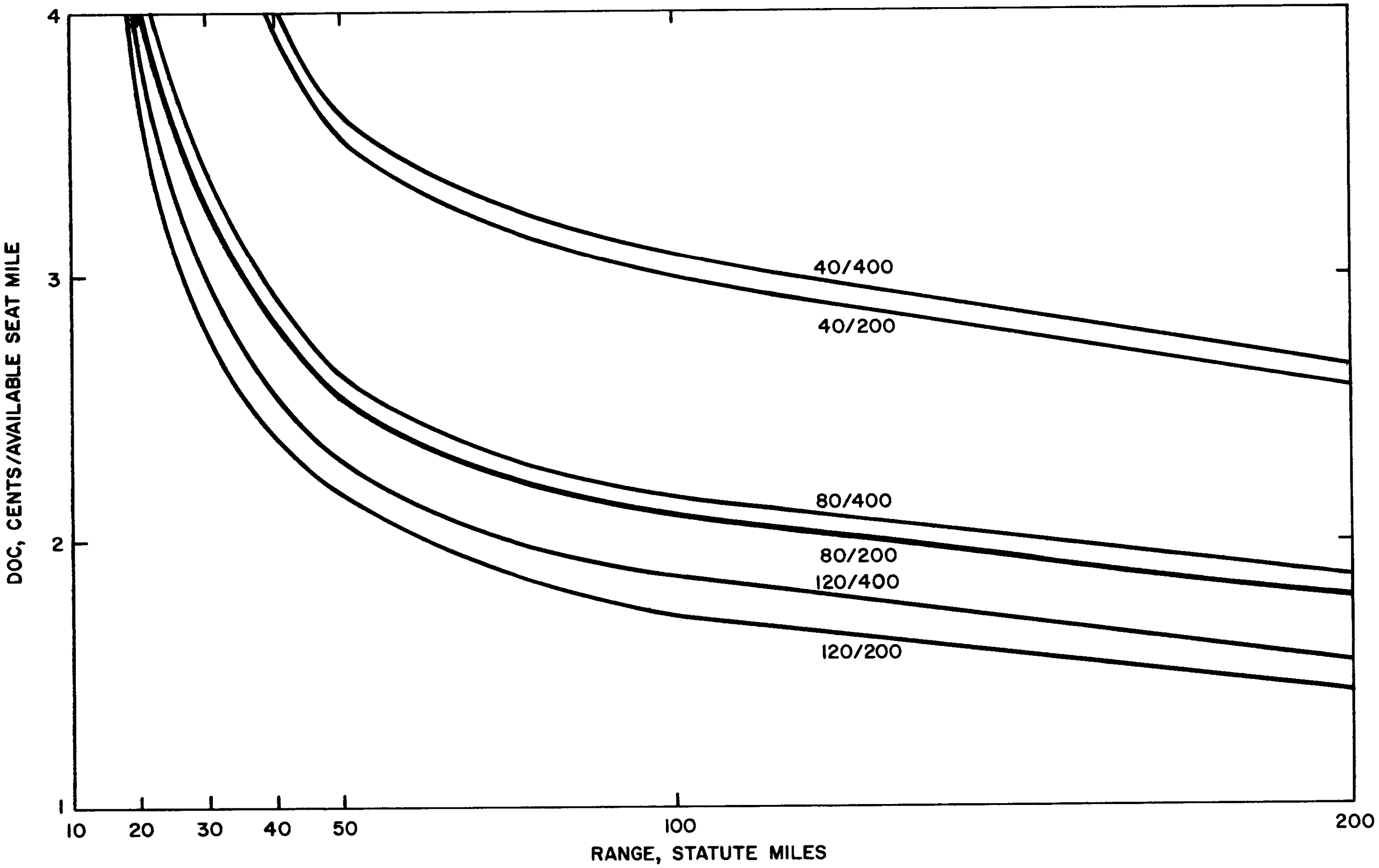

Figure II-8. STOL
PASSENGERS AND DESIGN RANGE VARIATION (PASS./DSGN RANGE)

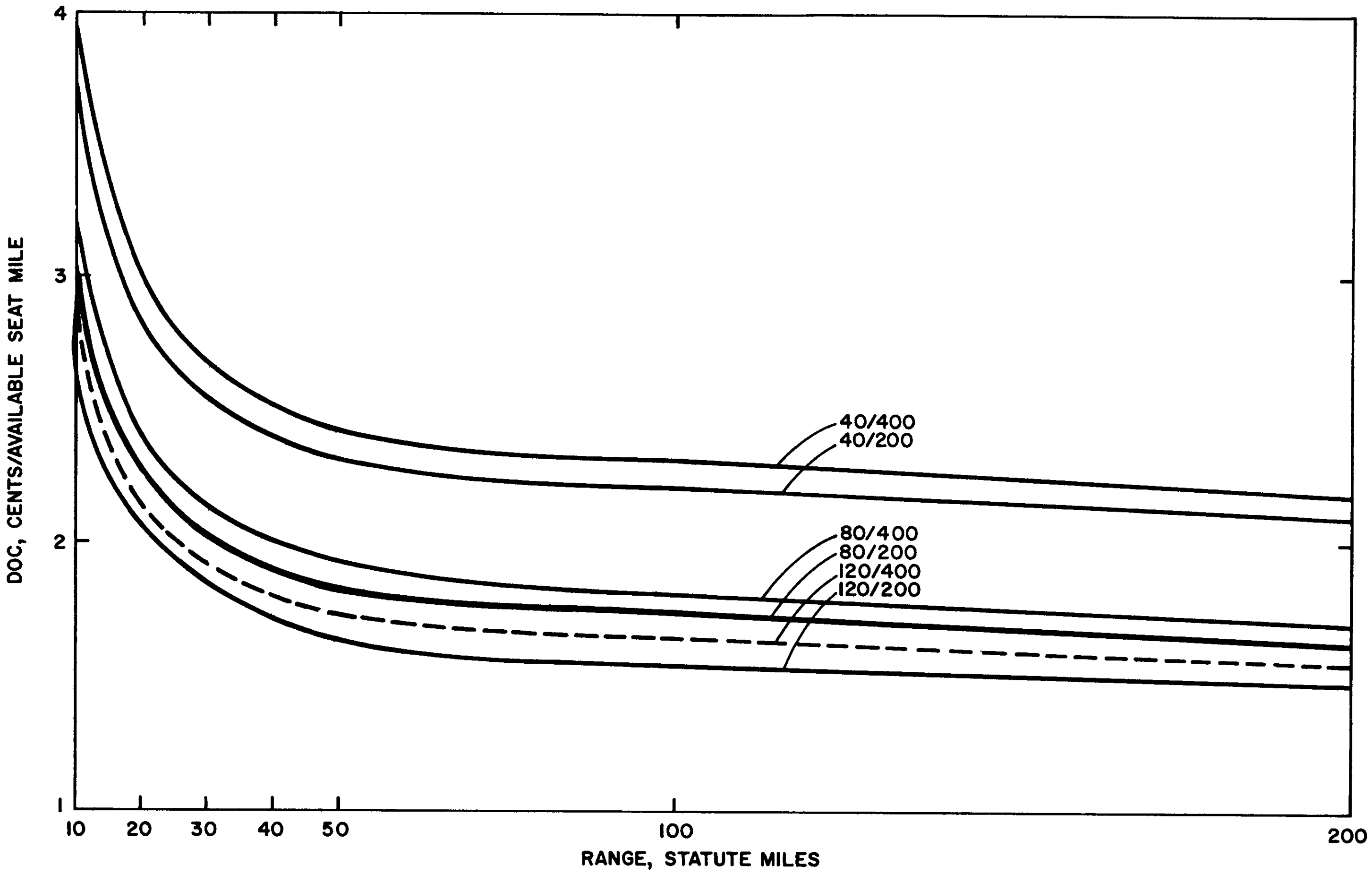

Figure II-9. TILT WING
WING SIZE AND DESIGN RANGE VARIATIONS (PASS./DSGN RANGE)

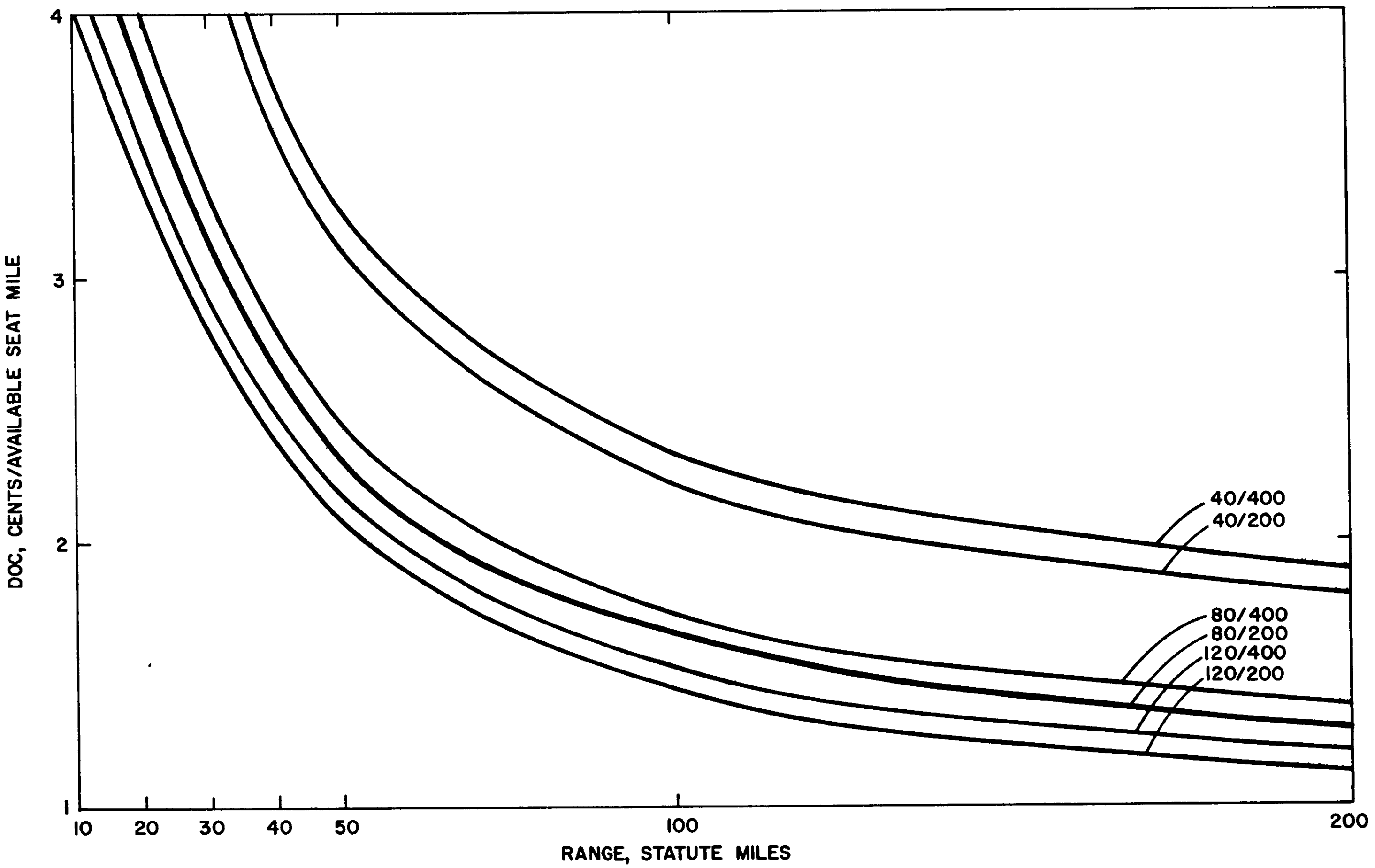

Figure II-10 JET LIFT
VARIATION OF PASSENGERS AND DESIGN RANGE (PASSENGERS/DESIGN RANGE)

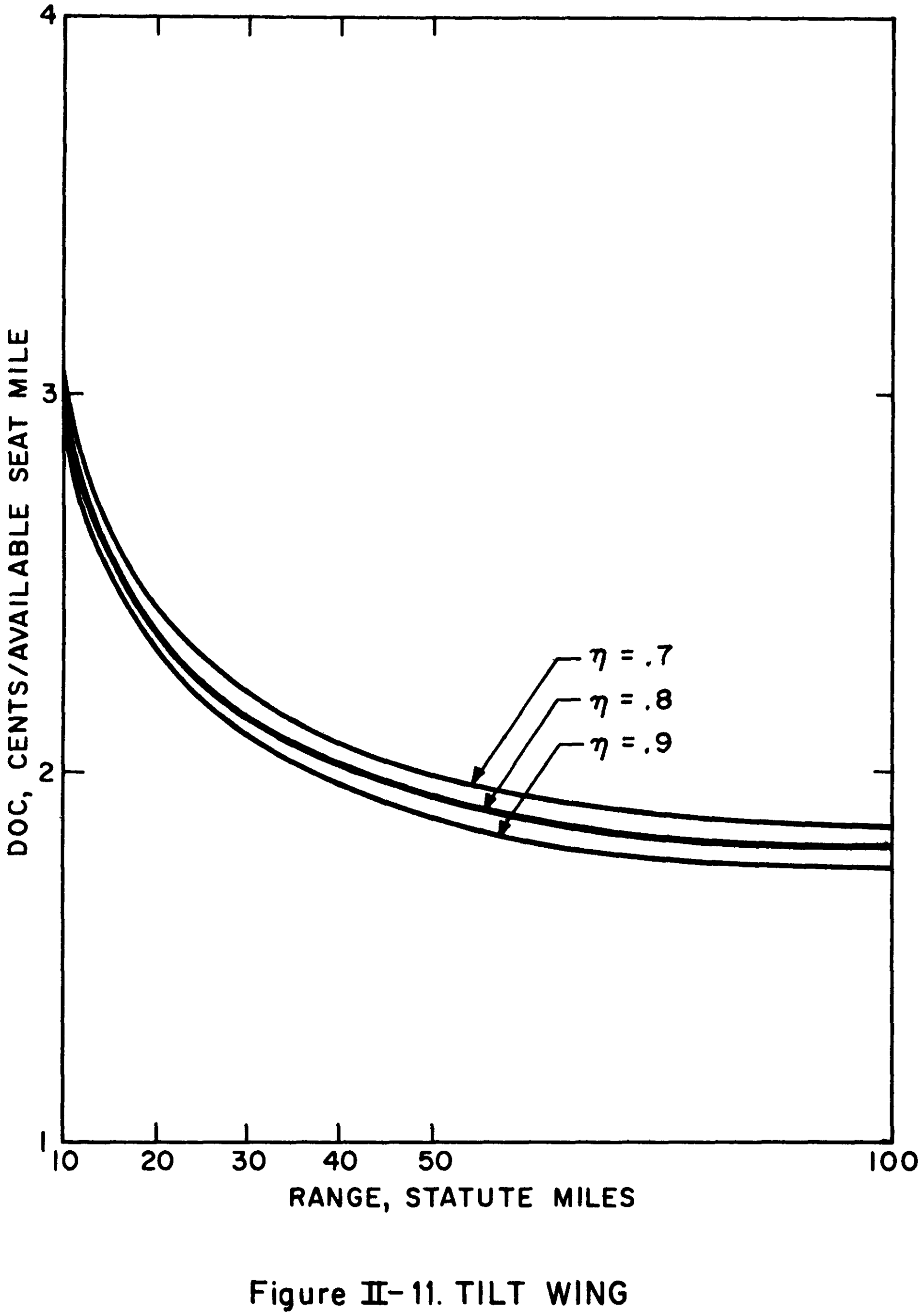

Figure II-11. TILT WING
PROPELLER EFFICIENCY VARIATION

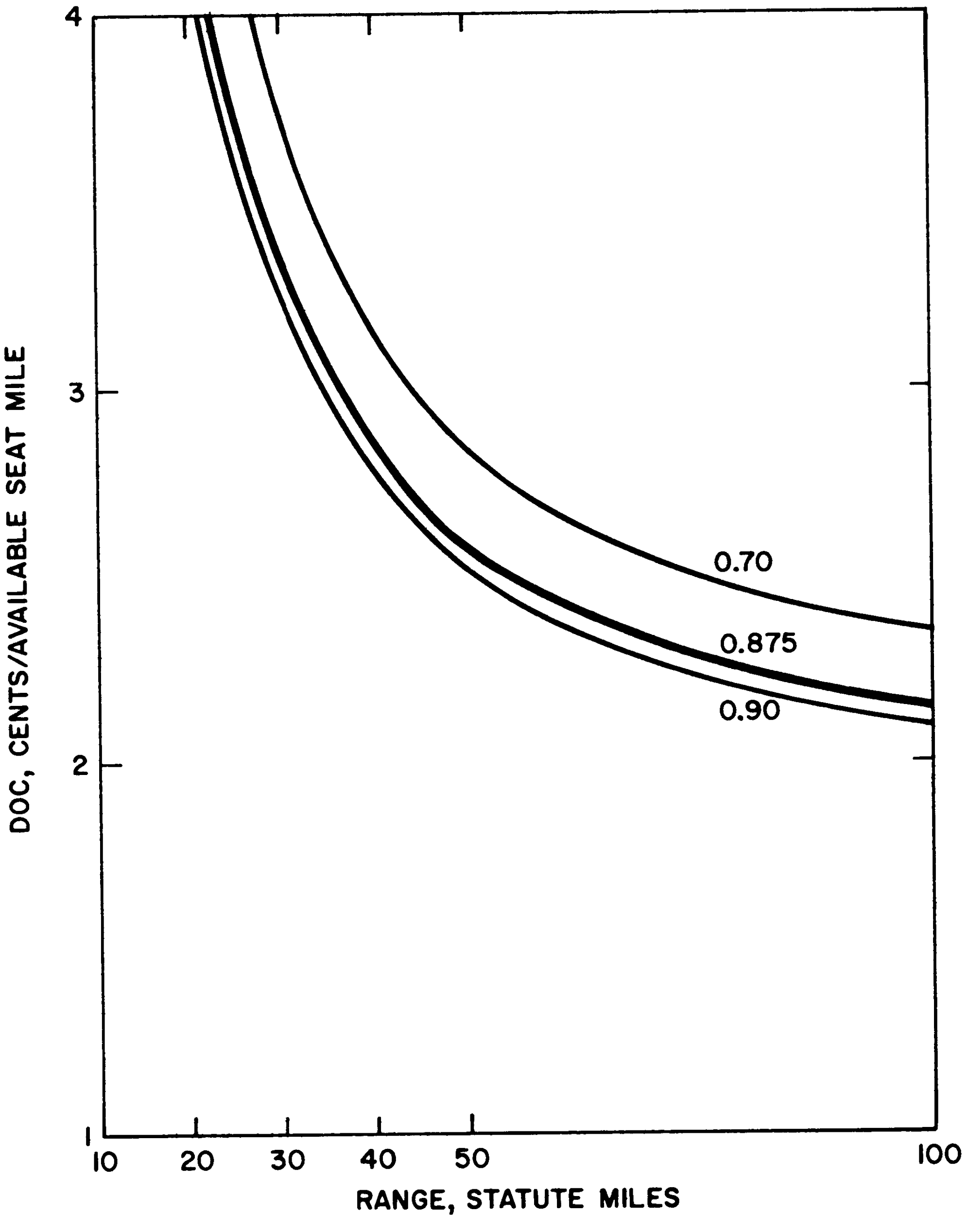

Figure II-12. STOL
PROPELLER EFFICENCY VARIATION

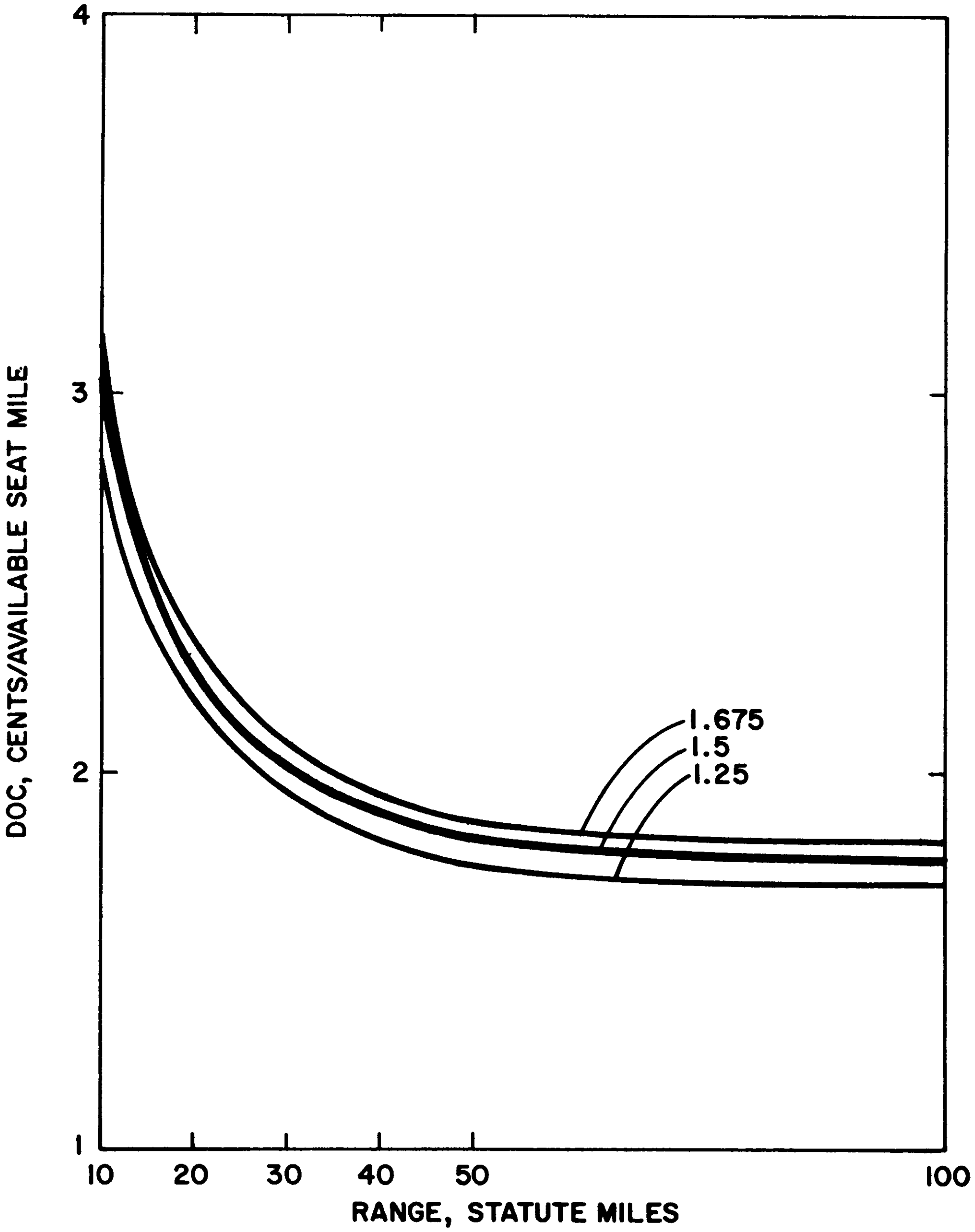

Figure II-13. TILT WING
ENGINE INSTALLATION FACTOR VARIATION

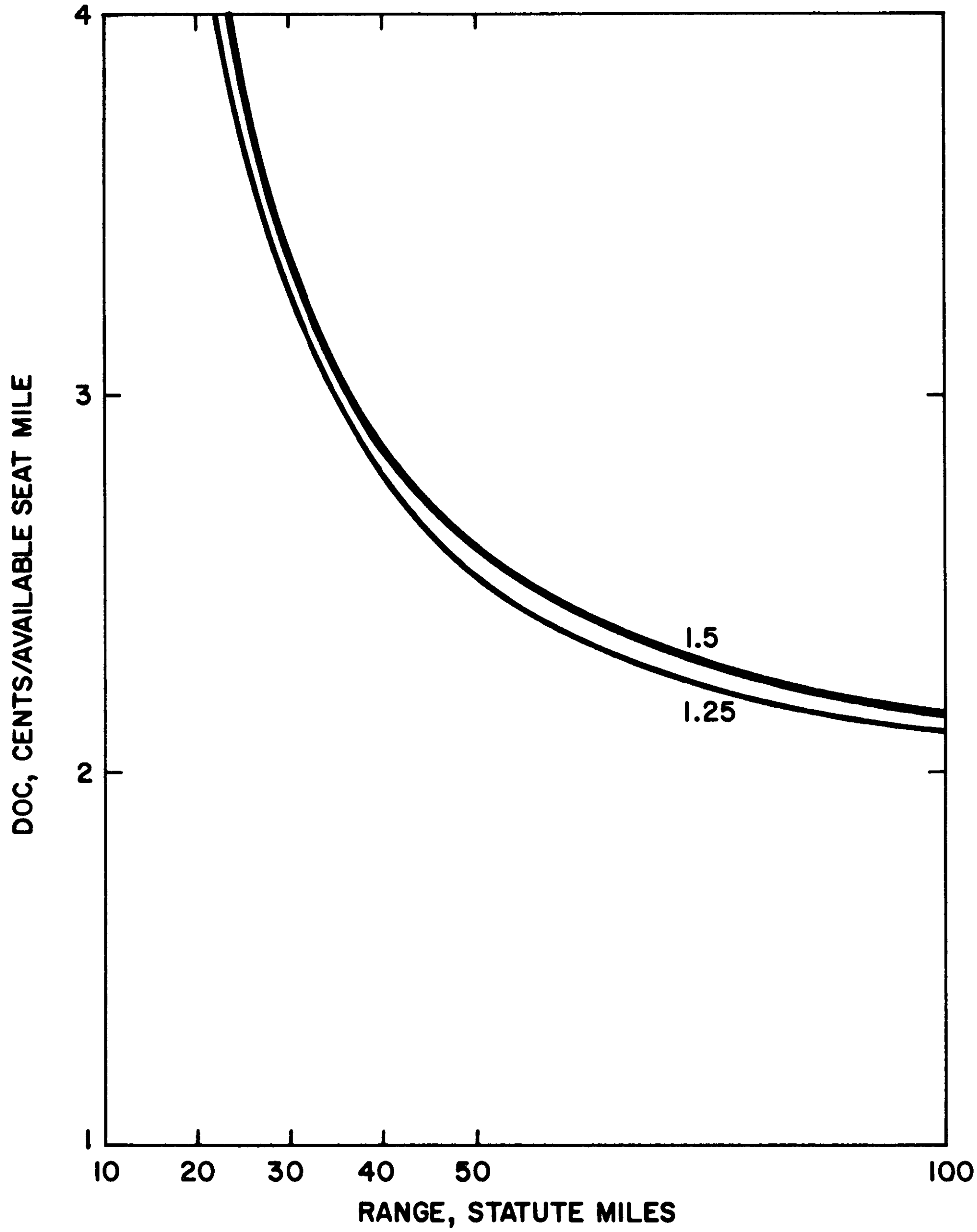

Figure II-14. STOL
ENGINE INSTALLATION FACTOR VARIATION

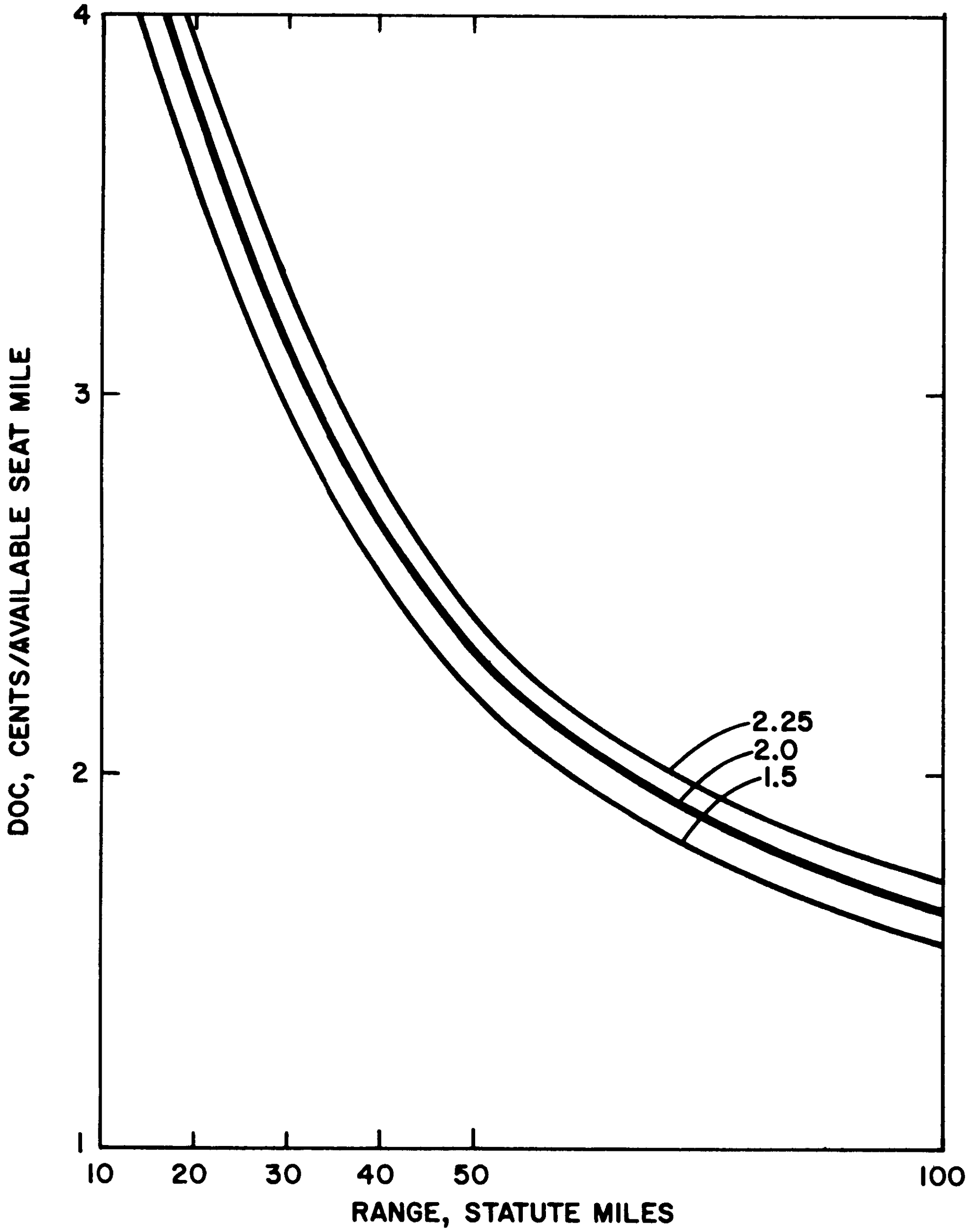

Figure II-15. JET LIFT
ENGINE INSTALLATION FACTOR VARIATION

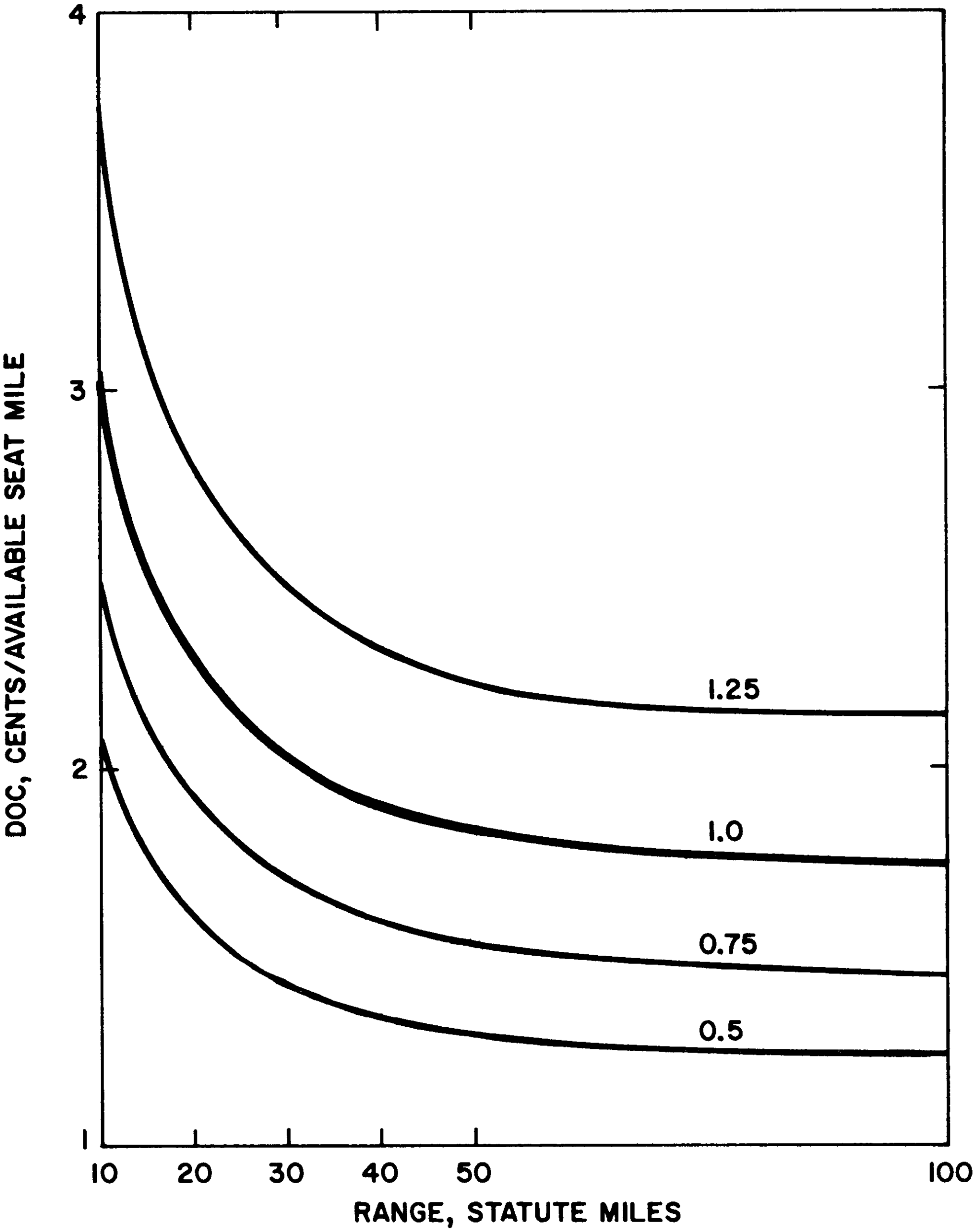

Figure II-16. TILT WING
STRUCTURAL WEIGHT FACTOR VARIATION

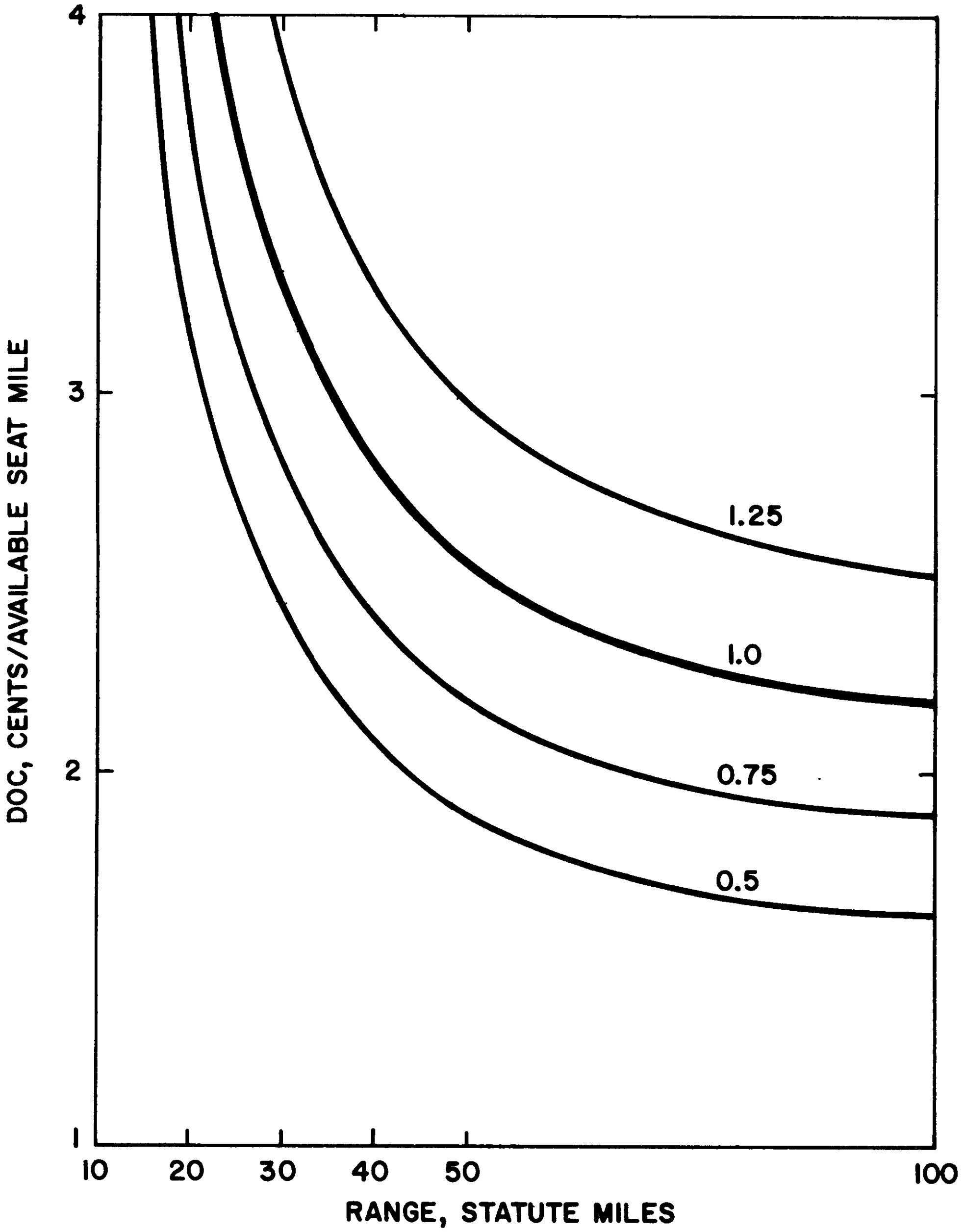

Figure II-17. STOL
STRUCTURAL WEIGHT FACTOR VARIATION

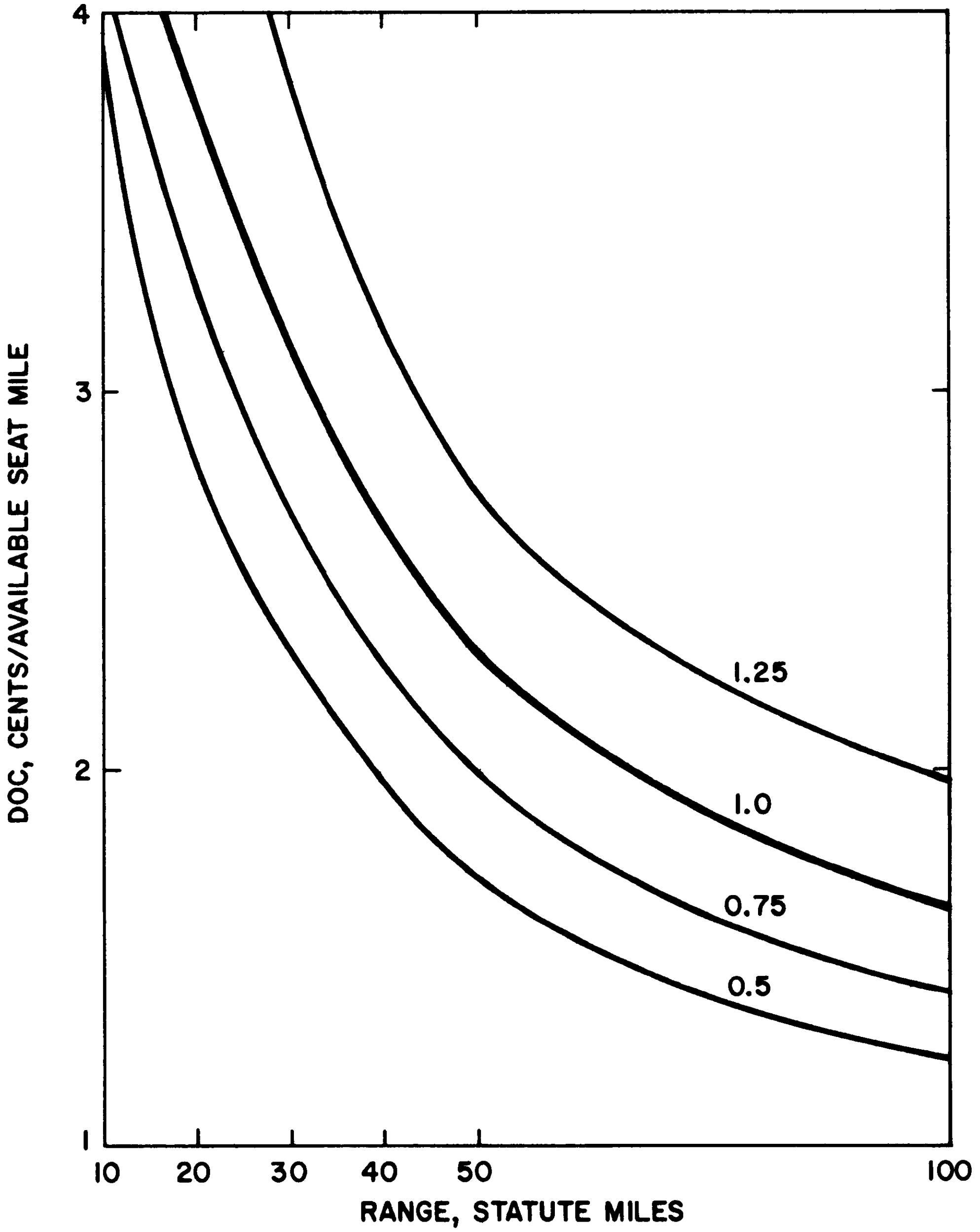

Figure II-18. JET LIFT
STRUCTURAL WEIGHT FACTOR VARIATION

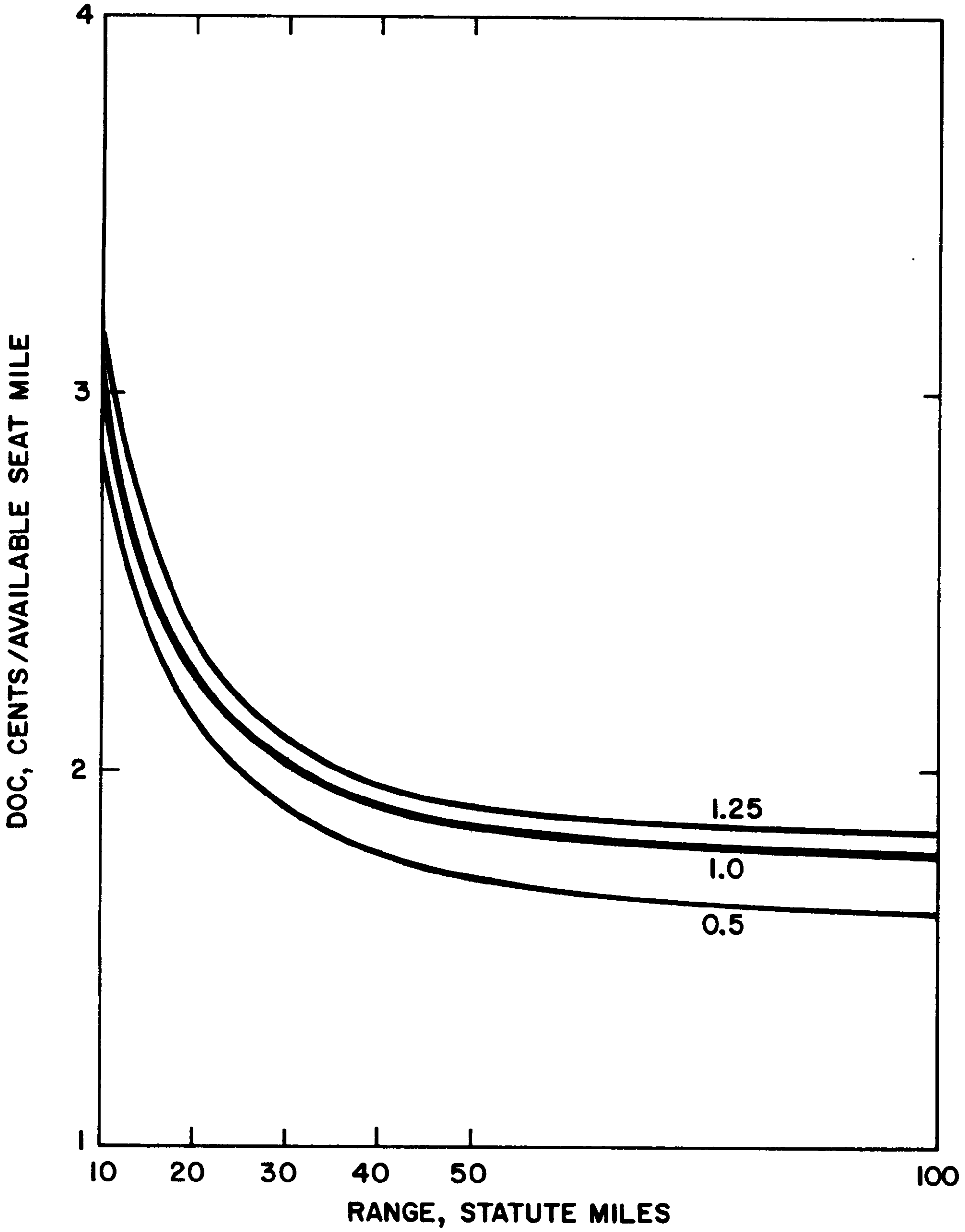

Figure II-19 TILT WING
TRANSMISSION WEIGHT VARIATION

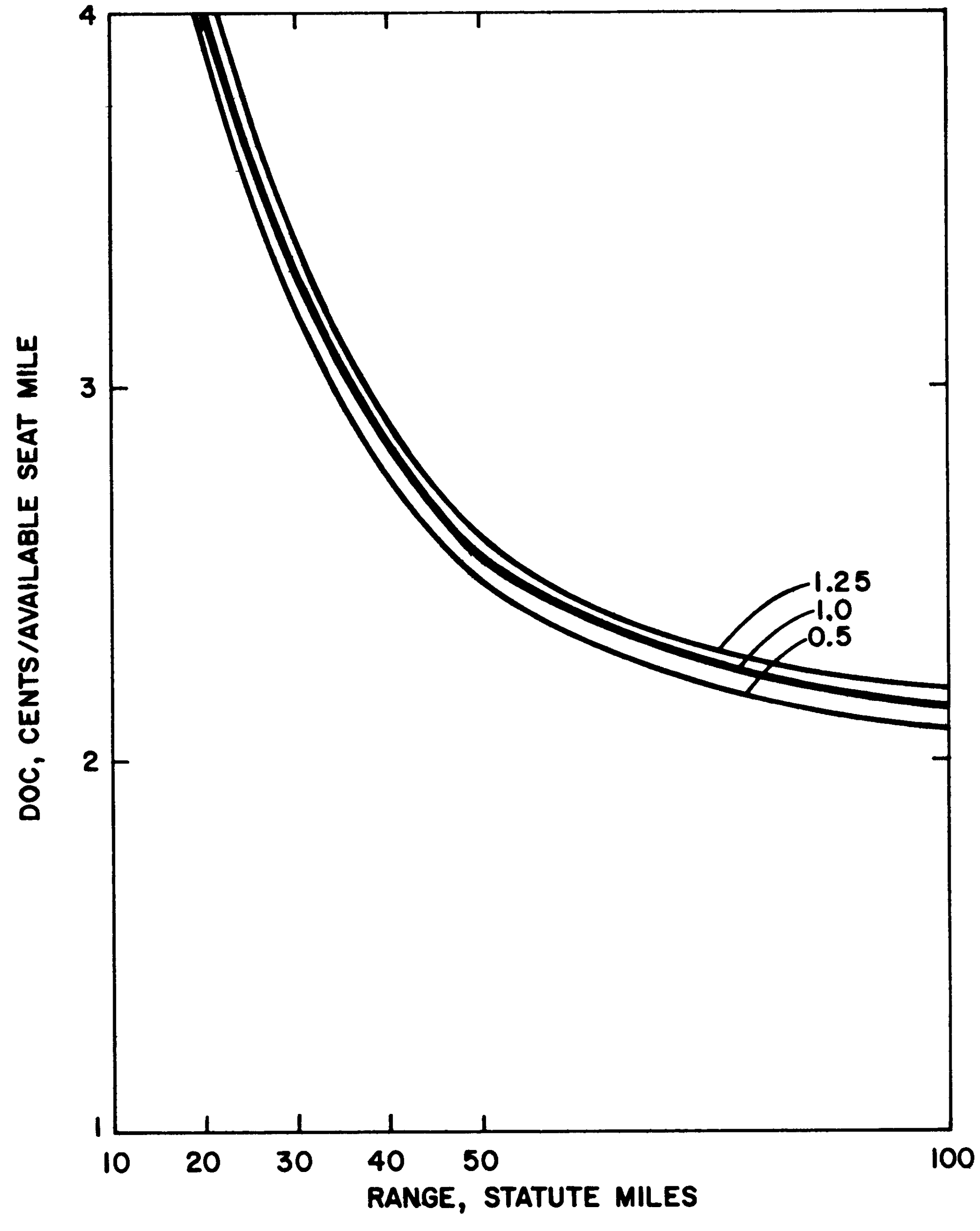

Figure II-20. STOL
TRANSMISSION WEIGHT FACTOR VARIATION

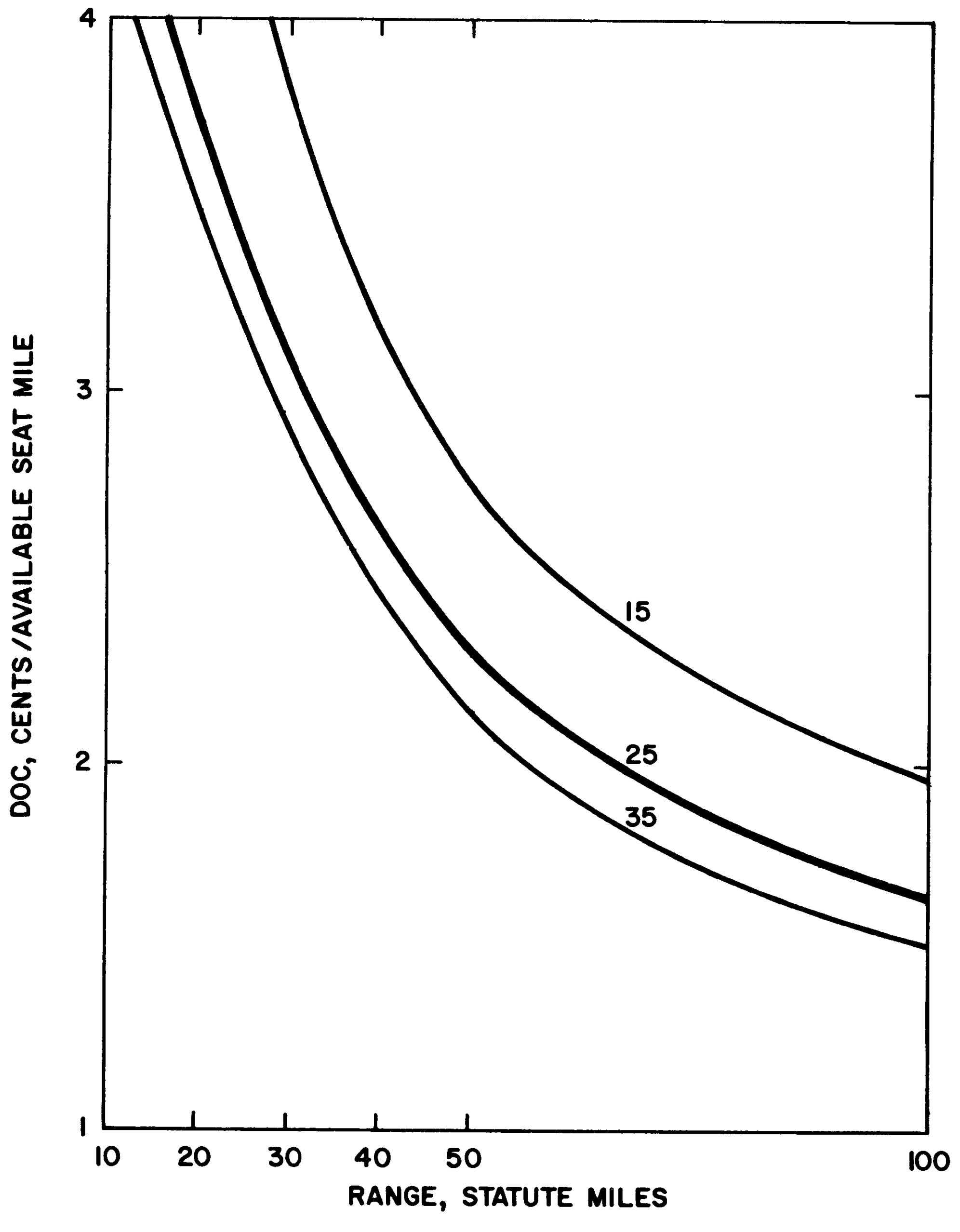

Figure II-21 JET LIFT
THRUST/WEIGHT OF LIFT ENGINE VARIATION

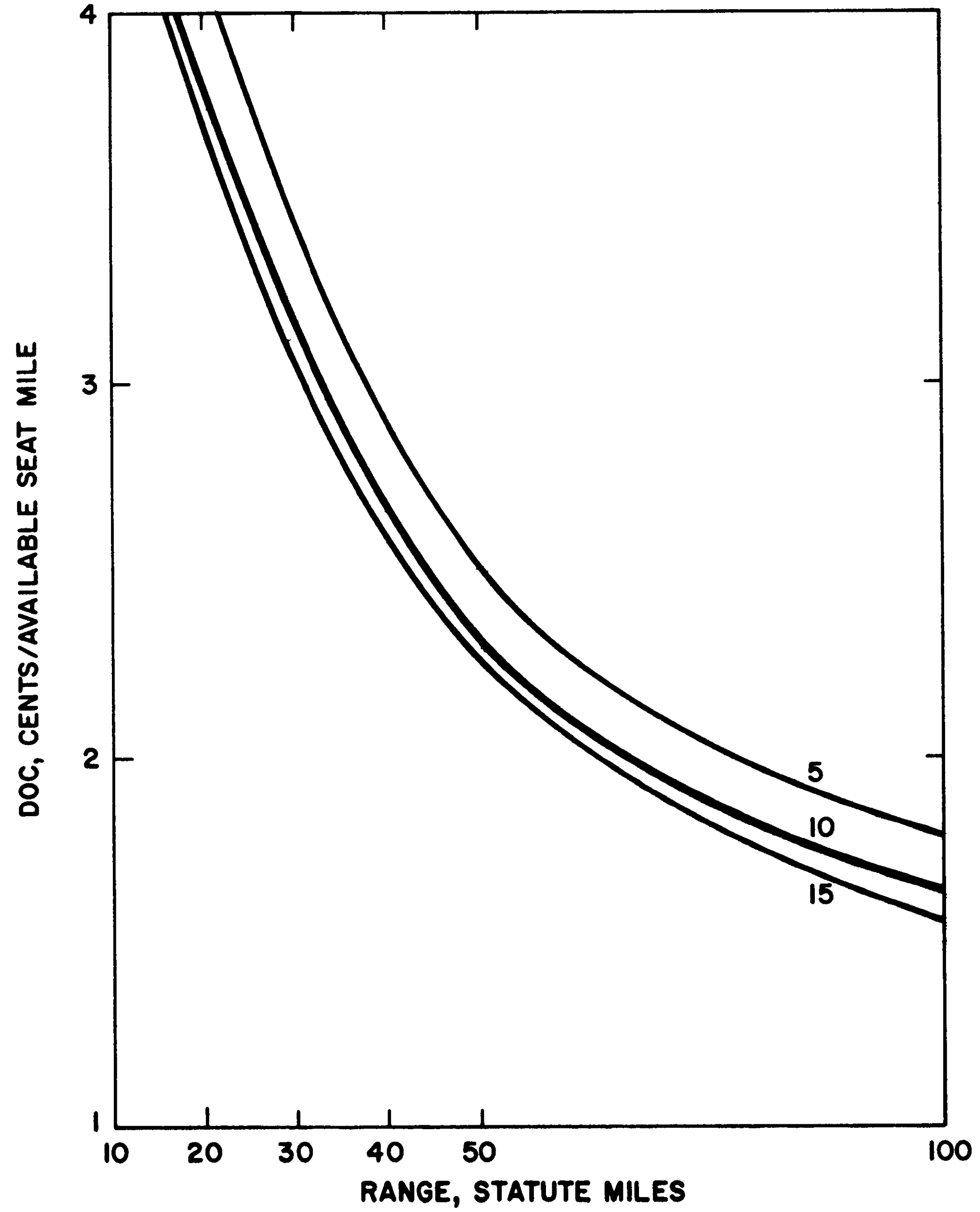

Figure II-22. JET LIFT
THRUST/WEIGHT OF CRUISE ENGINE VARIATION

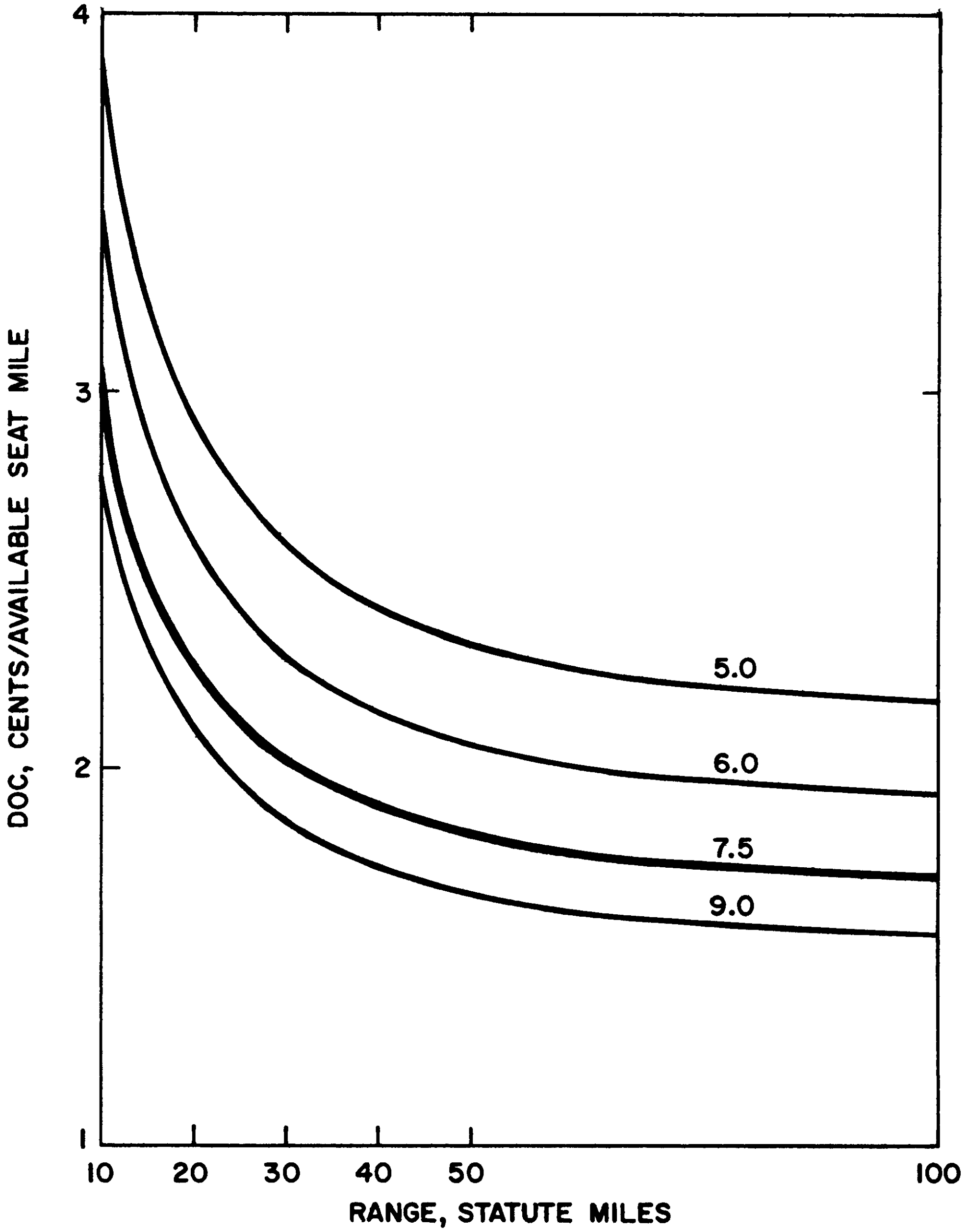

Figure II-23. TILT WING
ENGINE HP/LB VARIATION

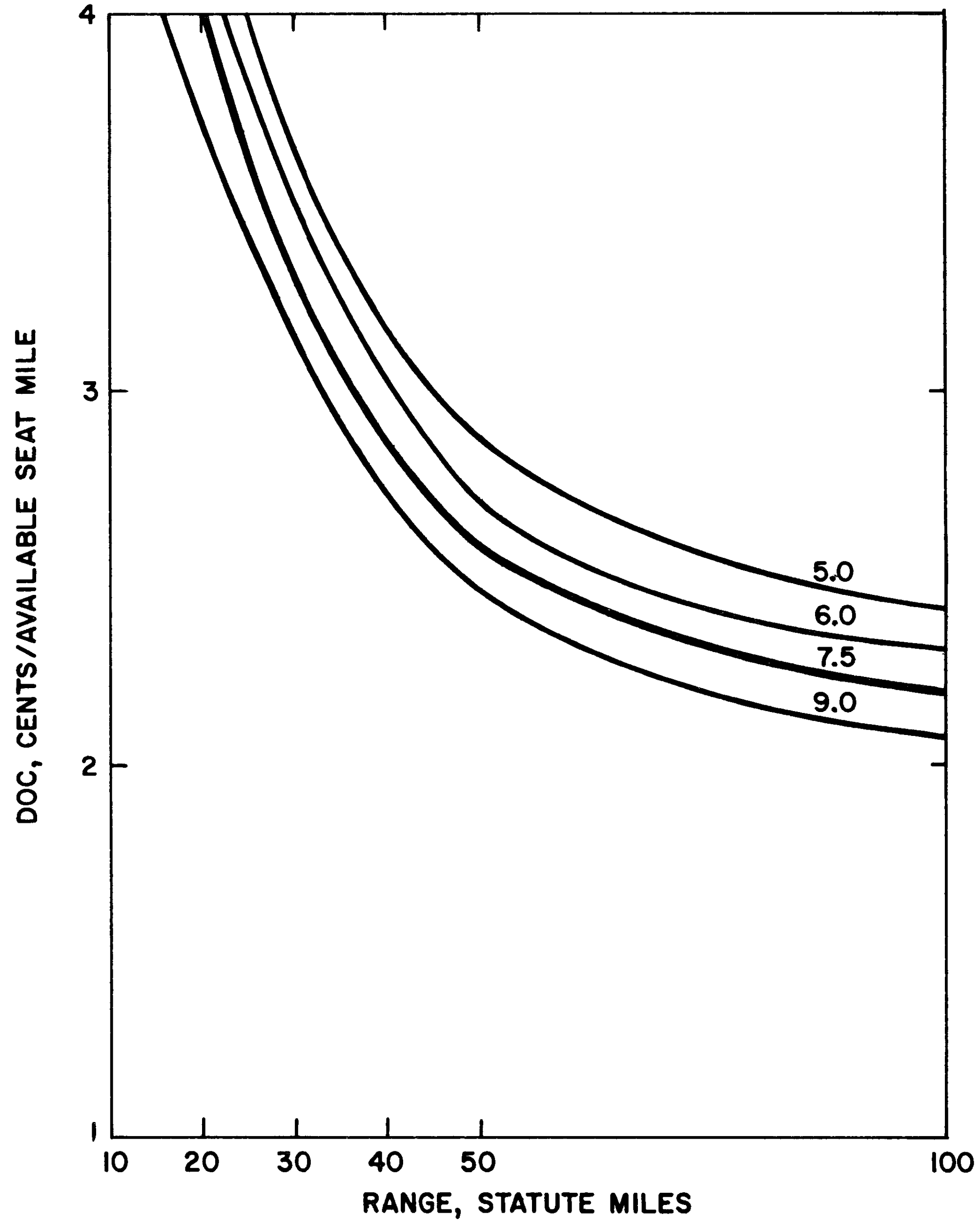

Figure II-24. STOL
ENGINE HP/LB VARIATION

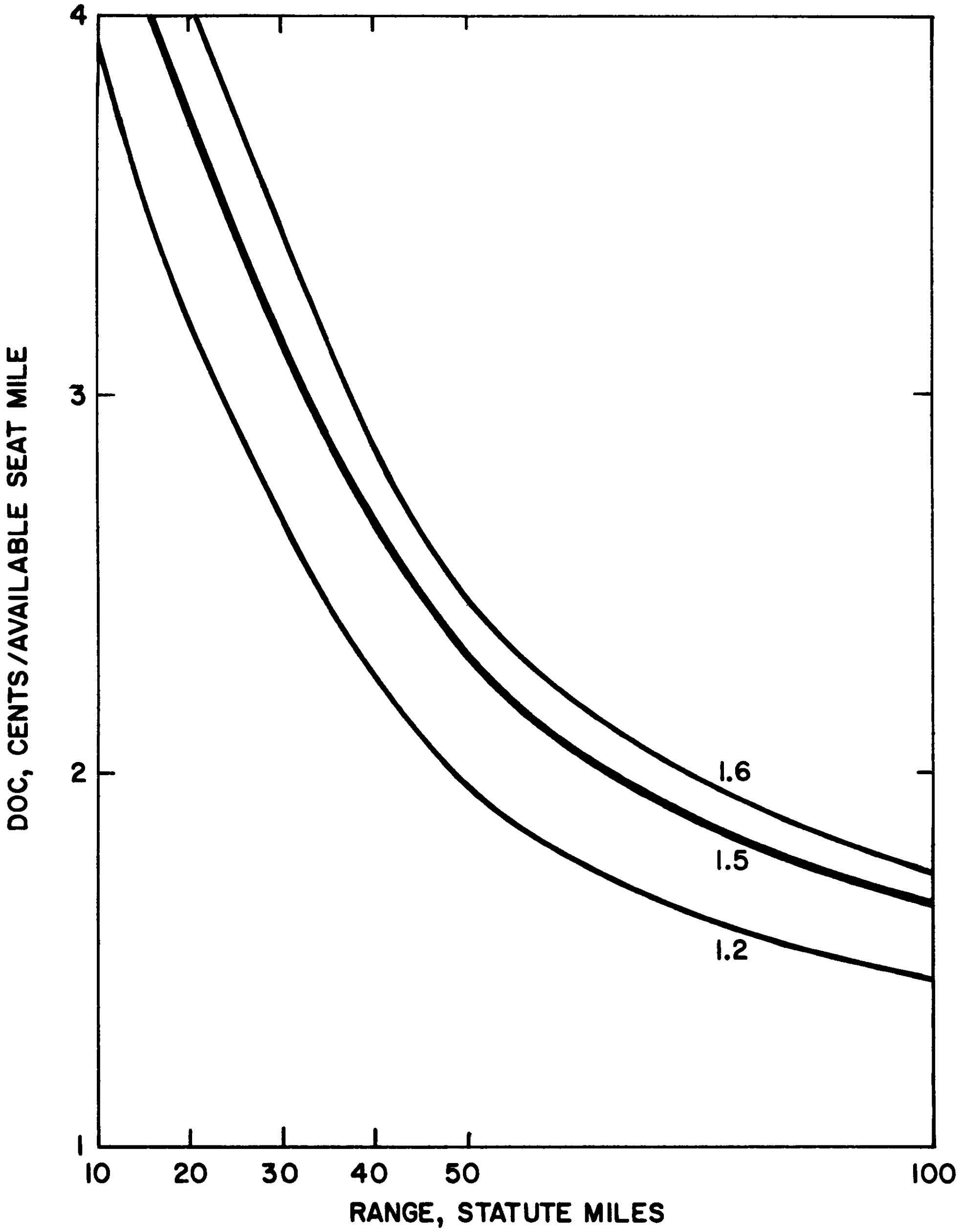

Figure II-25. JET LIFT
THRUST MARGIN VARIATION (TOTAL LIFT=GROSS WEIGHT x MARGIN)

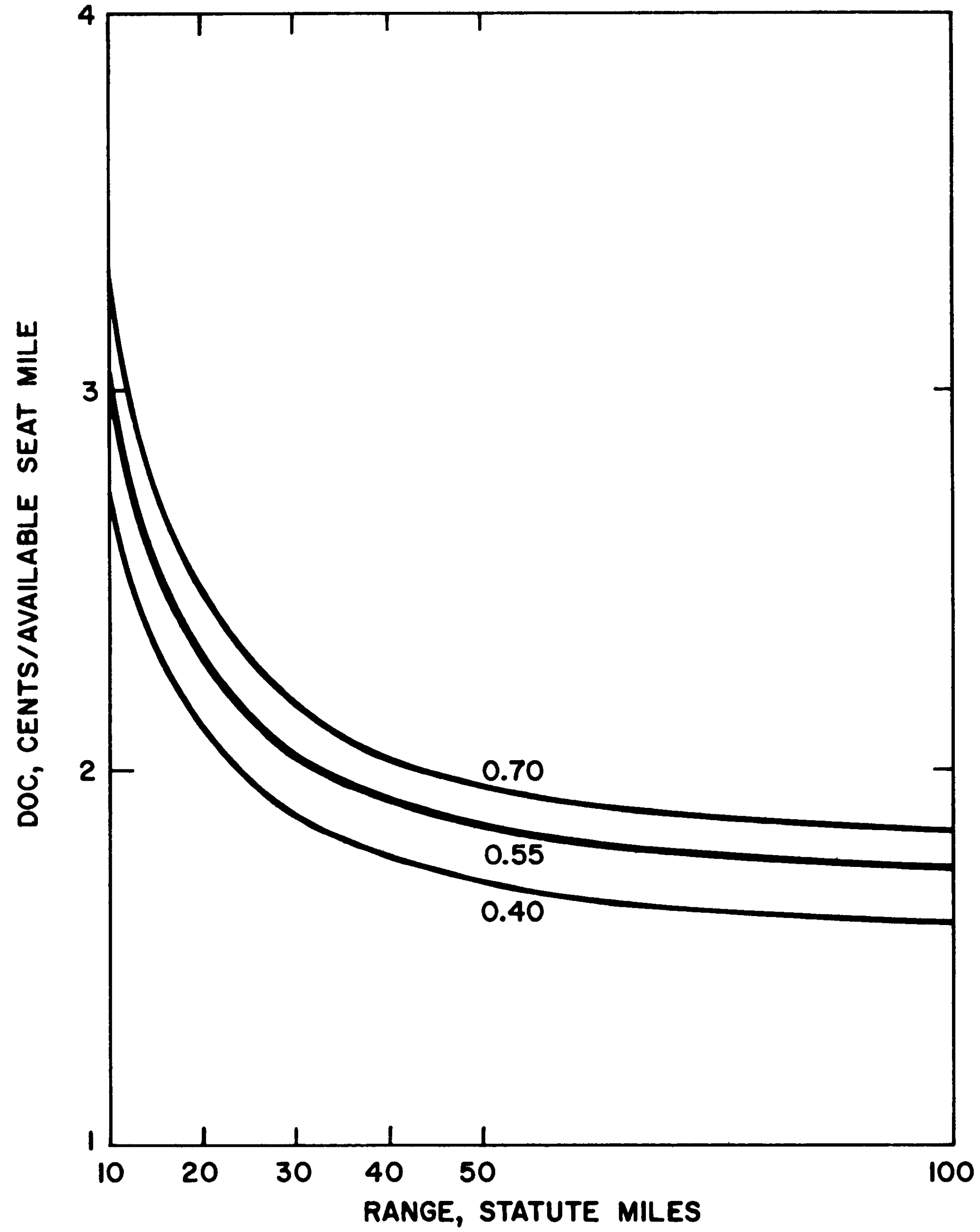

Figure II-26. TILT WING
SPECIFIC FUEL CONSUMPTION VARIATION (LB/HP/HR)

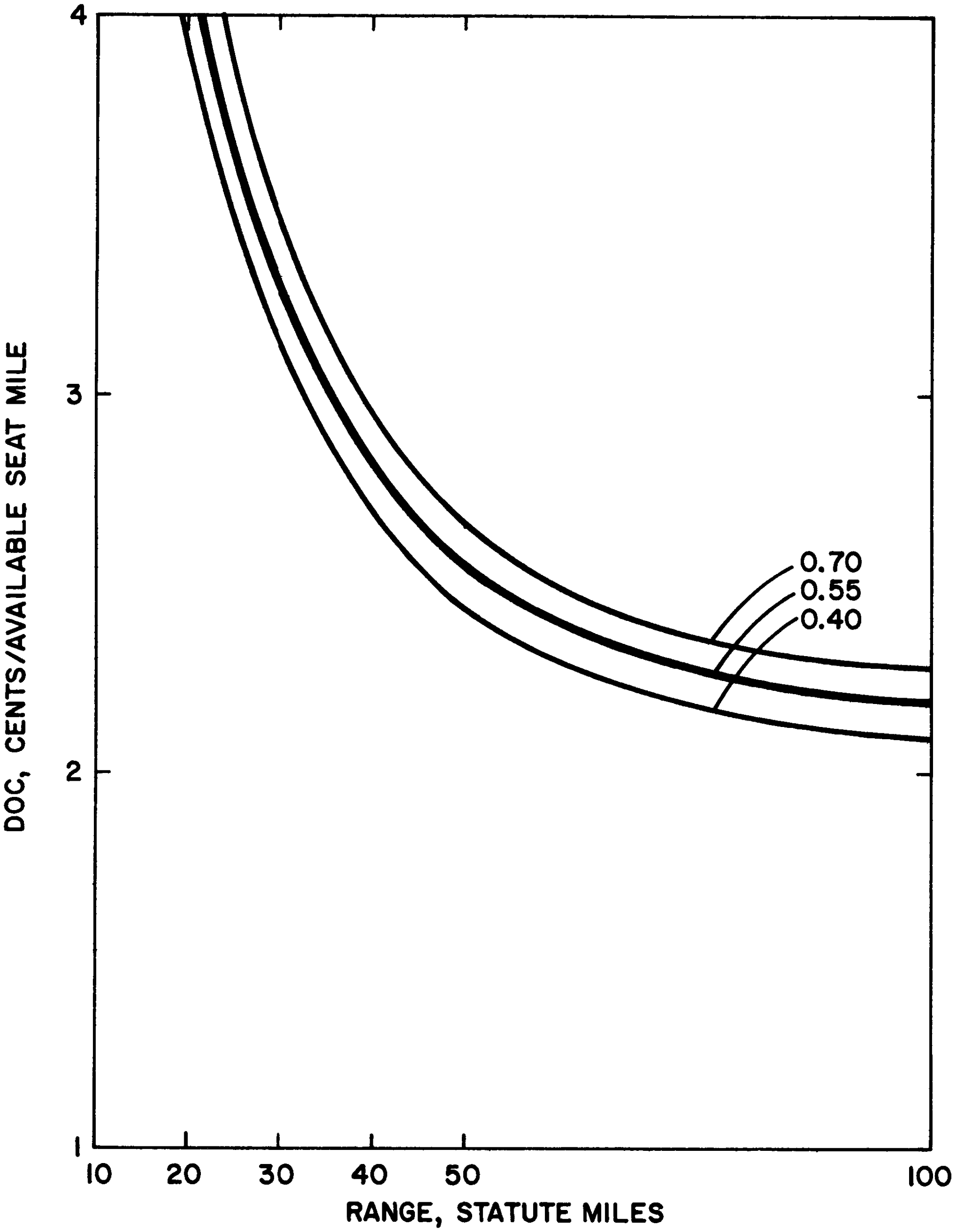

Figure II-27. STOL
SPECIFIC FUEL CONSUMPTION VARIATION (LB/HP/HR)

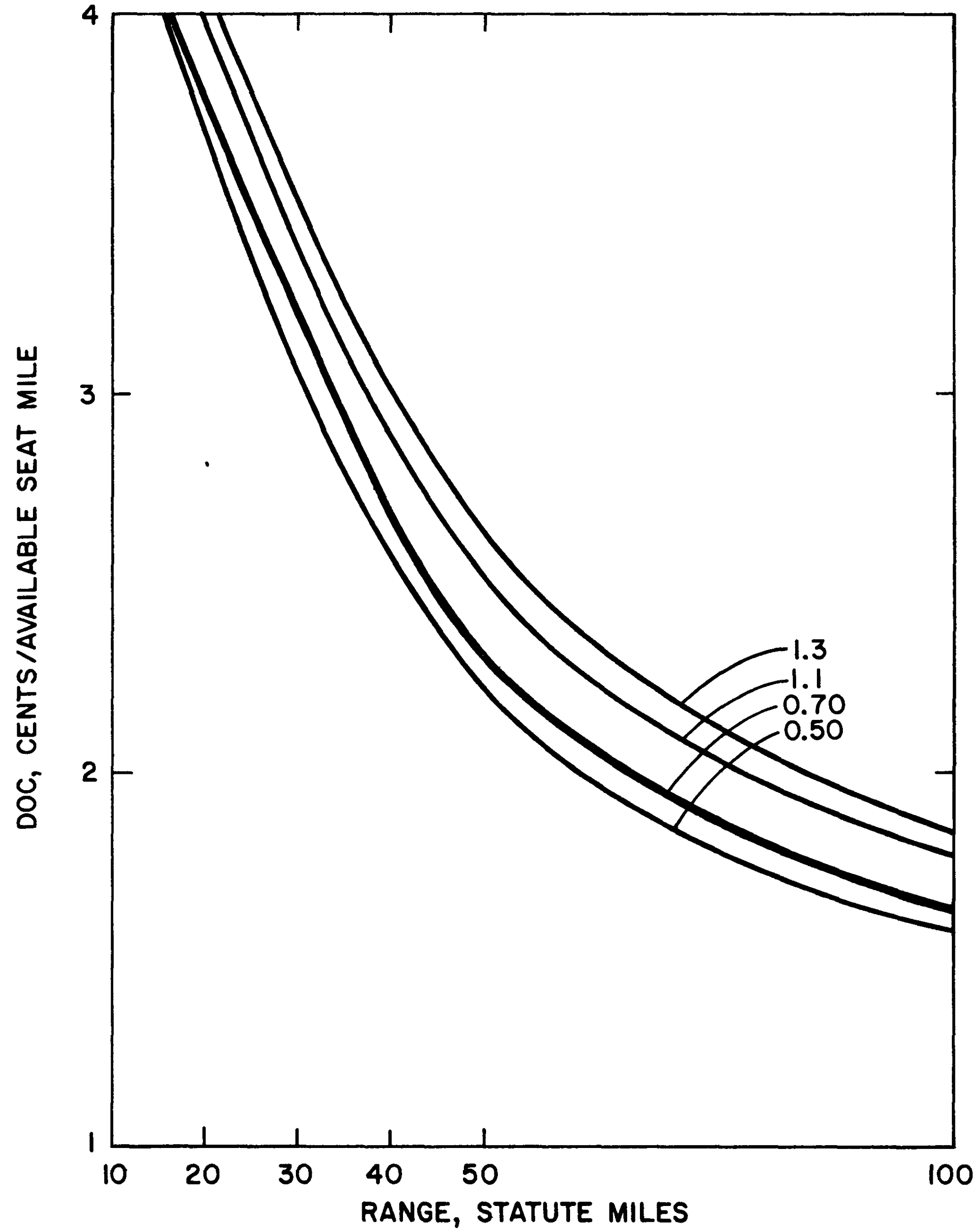

Figure II-28. JET LIFT
THRUST SPECIFIC FUEL CONSUMPTION (LIFT ENGINE) VARIATION

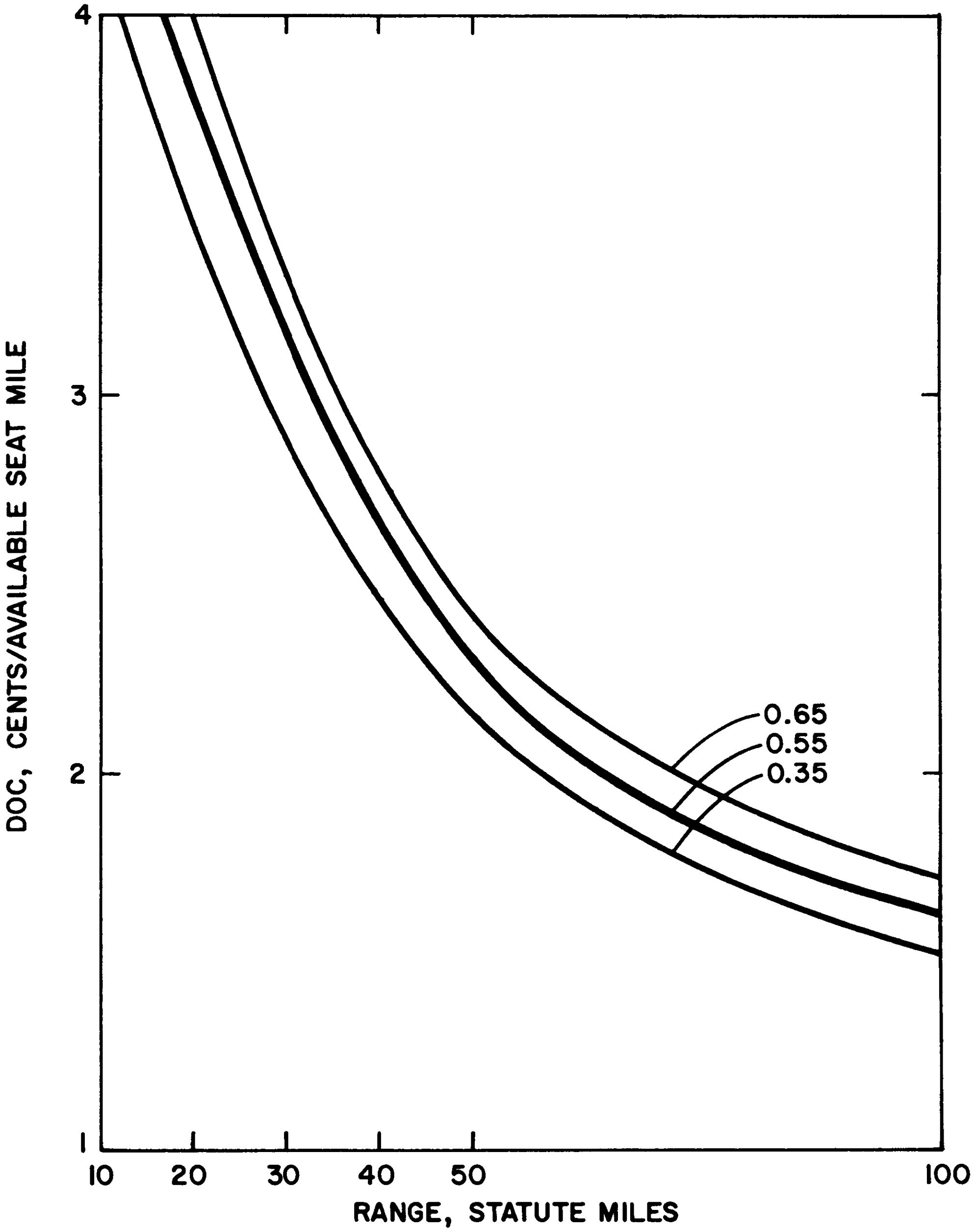

Figure II-29. JET LIFT
THRUST SPECIFIC FUEL CONSUMPTION (CRUISE ENGINE) VARIATION

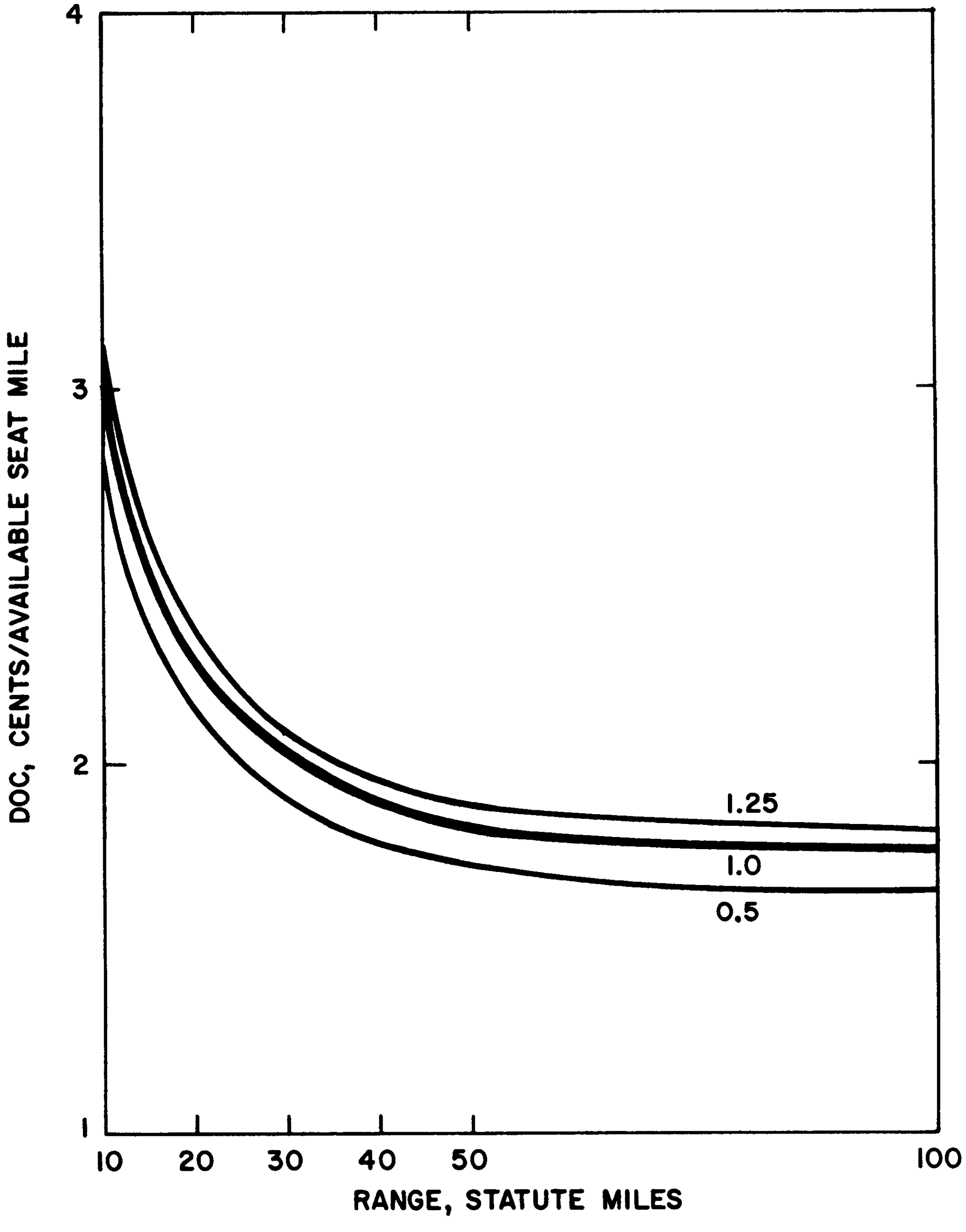

Figure II-30. TILT WING
PROPELLER WEIGHT FACTOR VARIATION

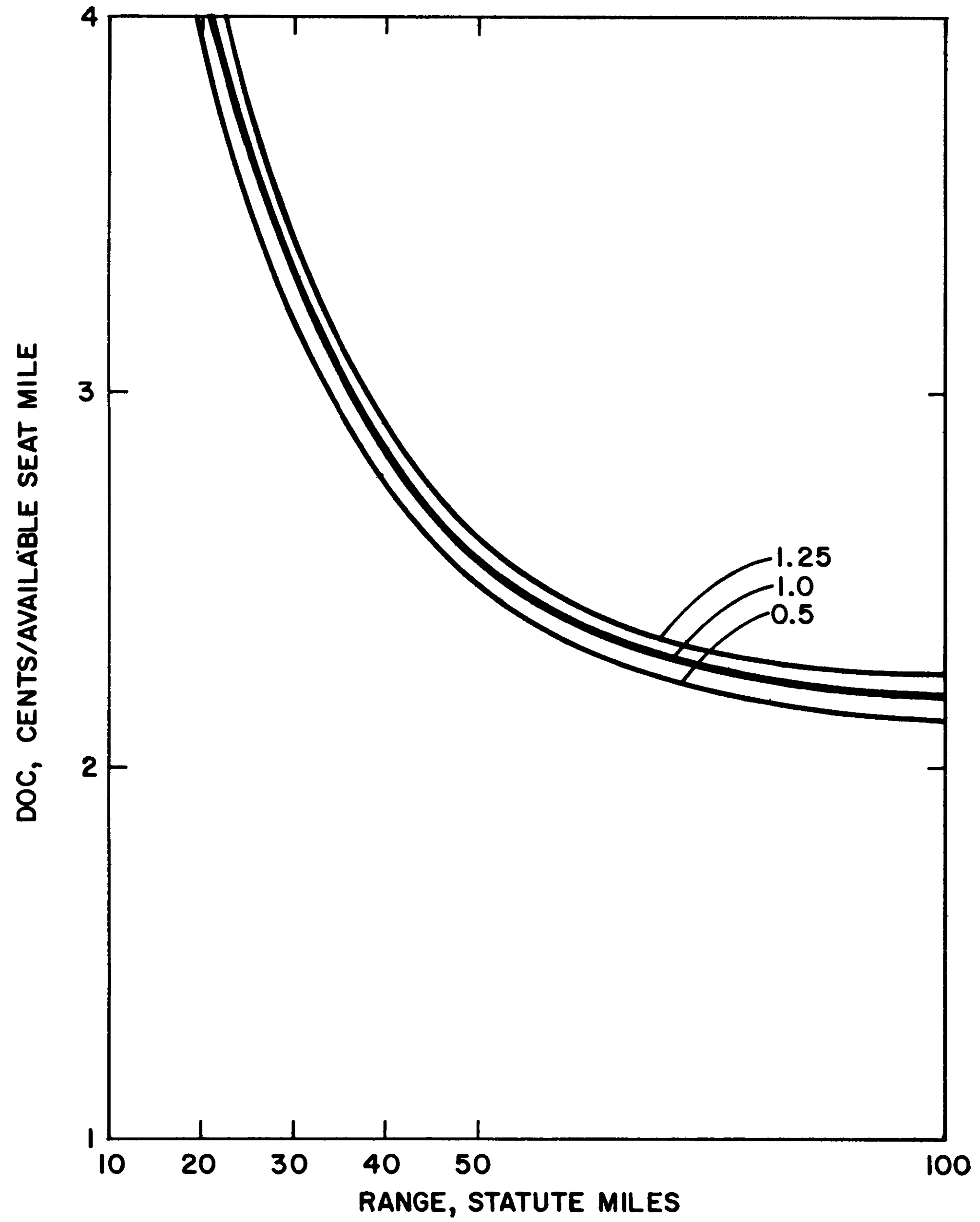

Figure II-31. STOL
PROPELLER WEIGHT FACTOR VARIATION

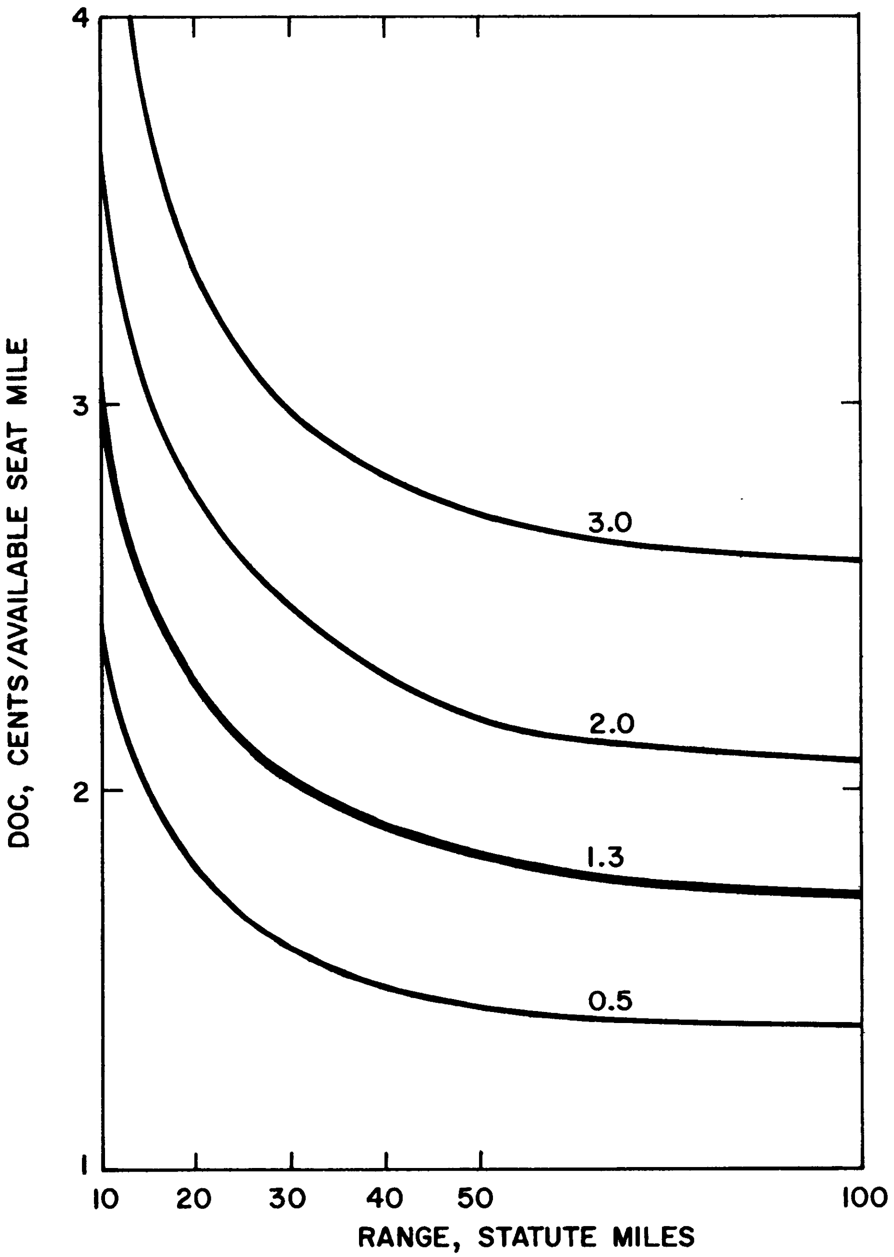

Figure II-32. TILT WING MAINTENANCE FACTOR VARIATION

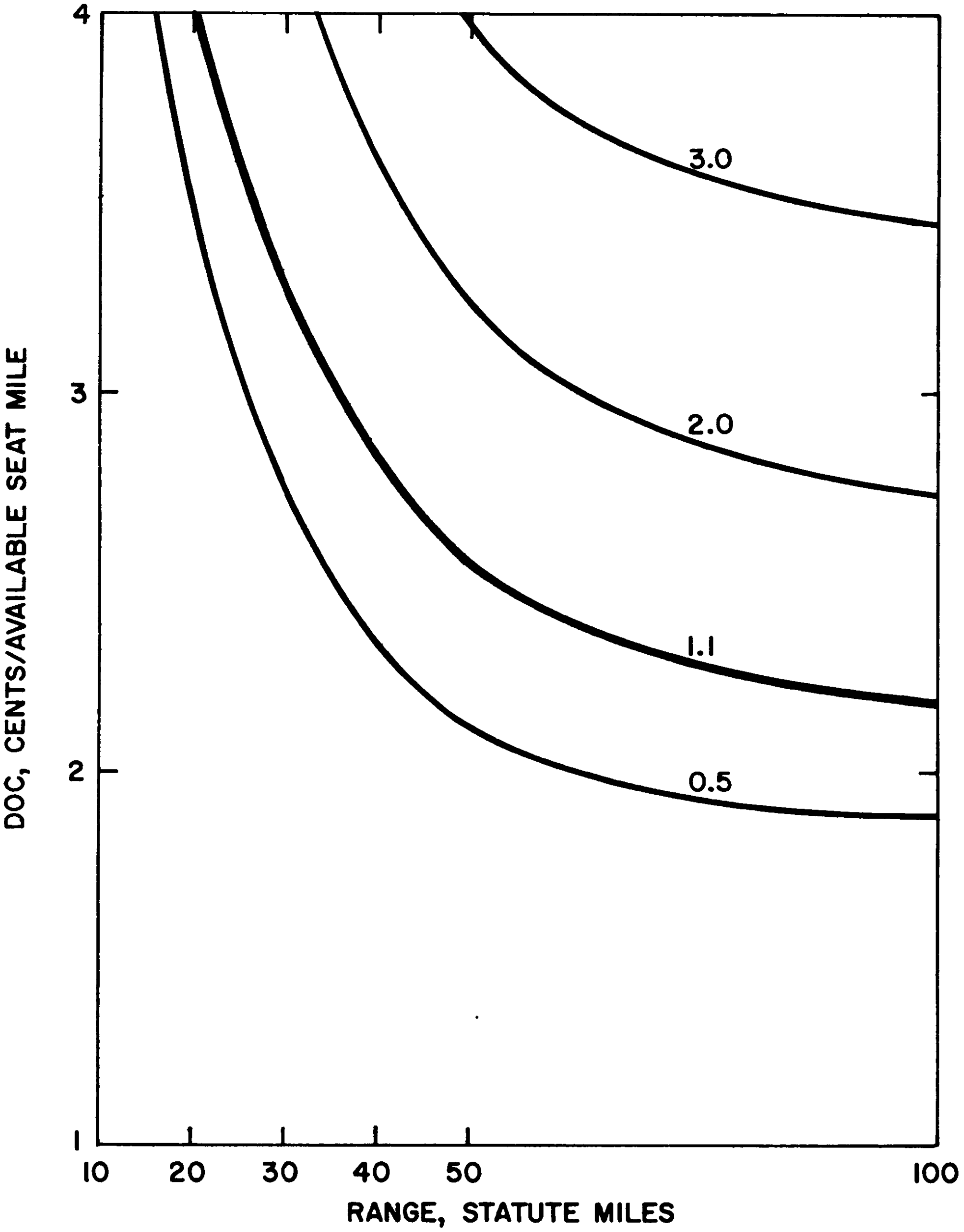

Figure II-33. STOL
MAINTENANCE FACTOR VARIATION

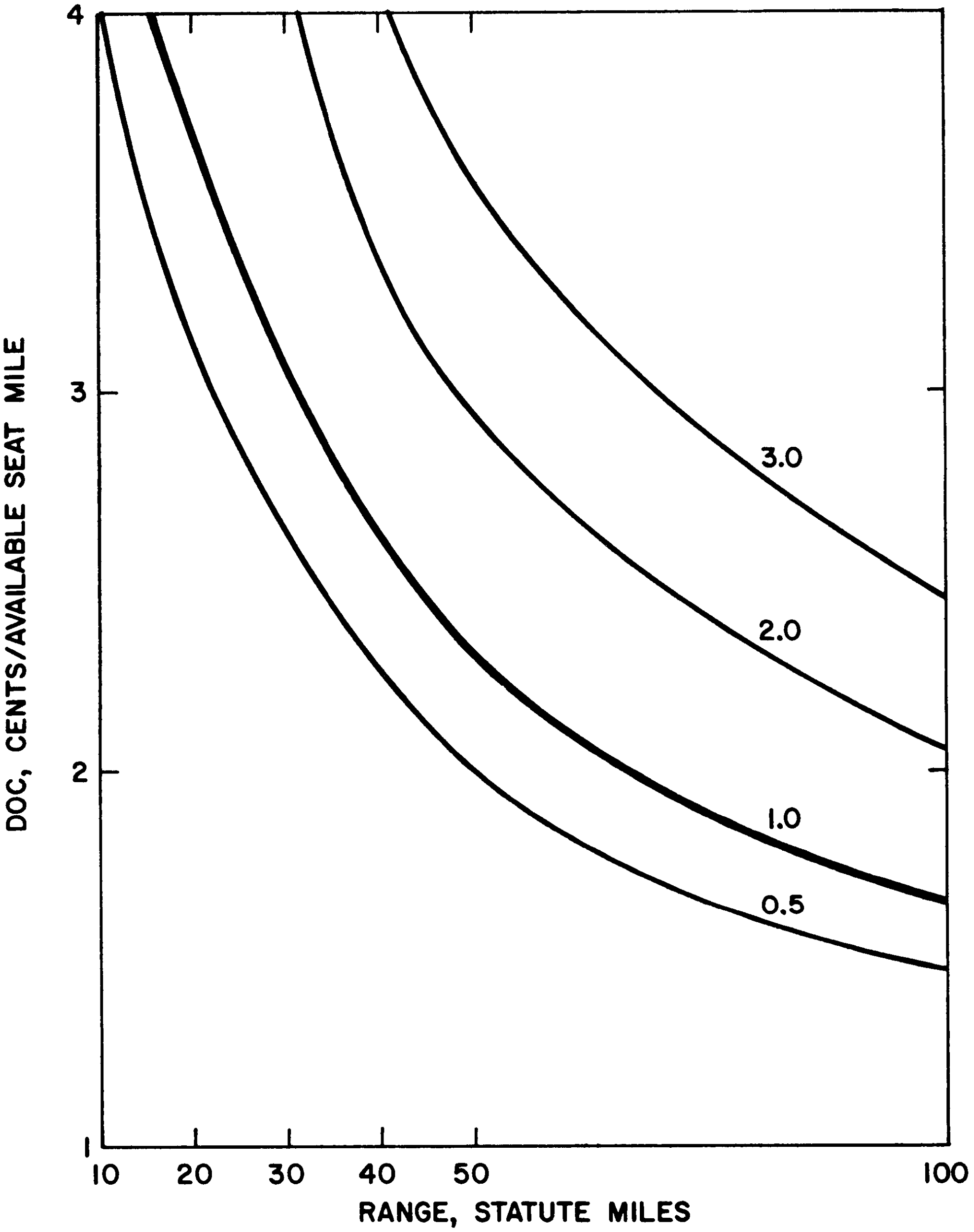

Figure II-34. JET LIFT
MAINTENANCE FACTOR VARIATION

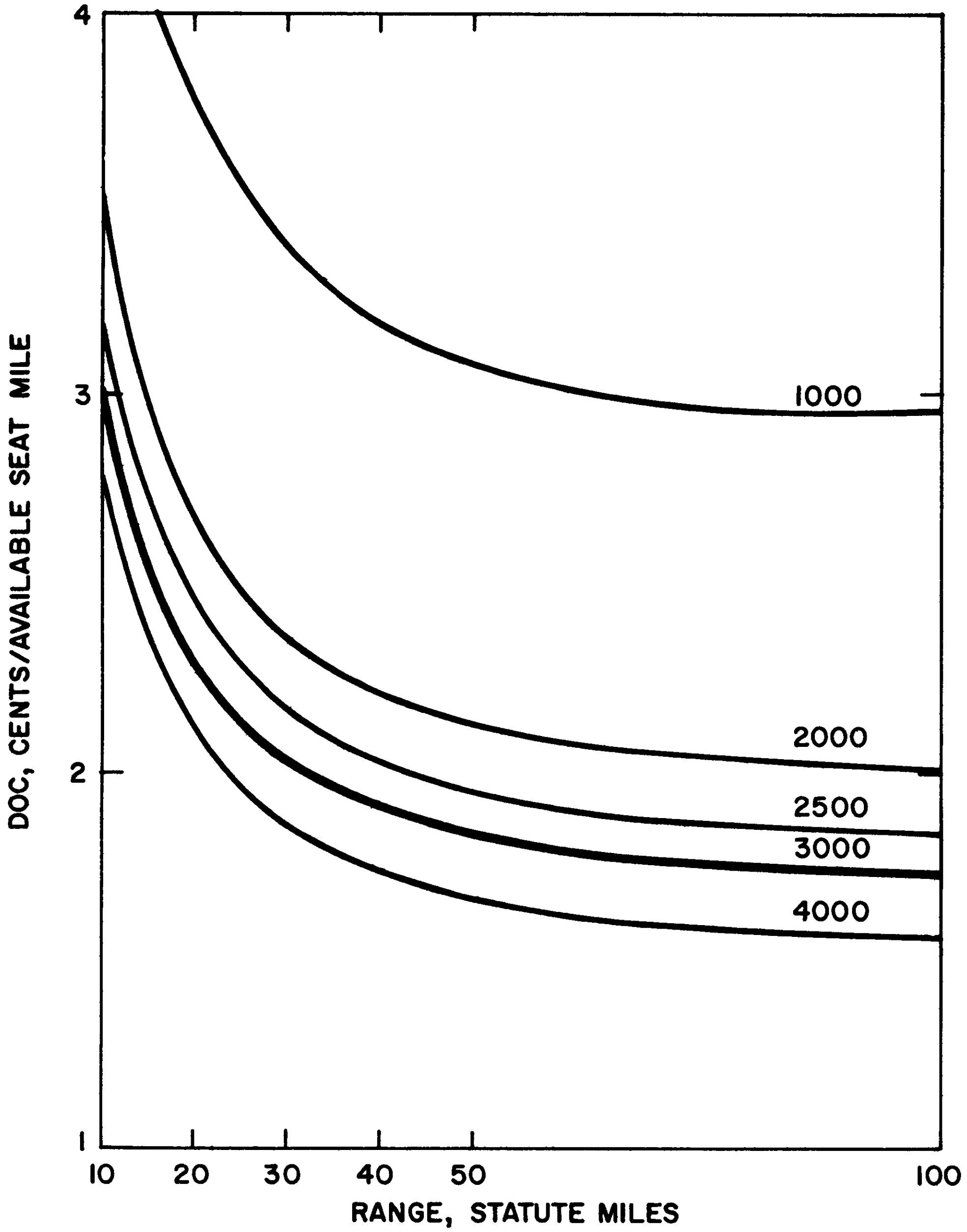

Figure II-35. TILT WING
ANNUAL UTILIZATION VARIATION (HRS)

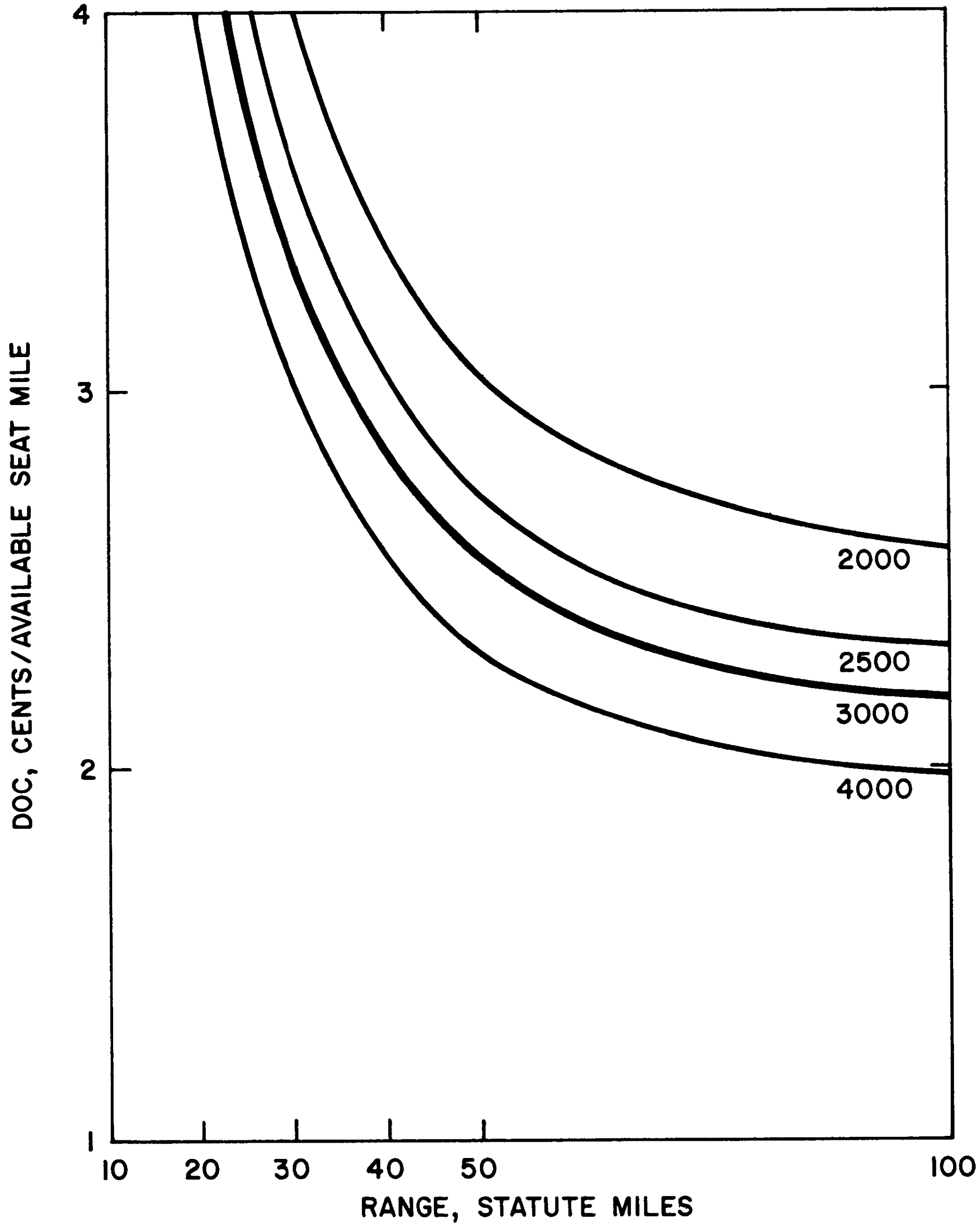

Figure II-36 STOL
ANNUAL UTILIZATION VARIATION (HRS)

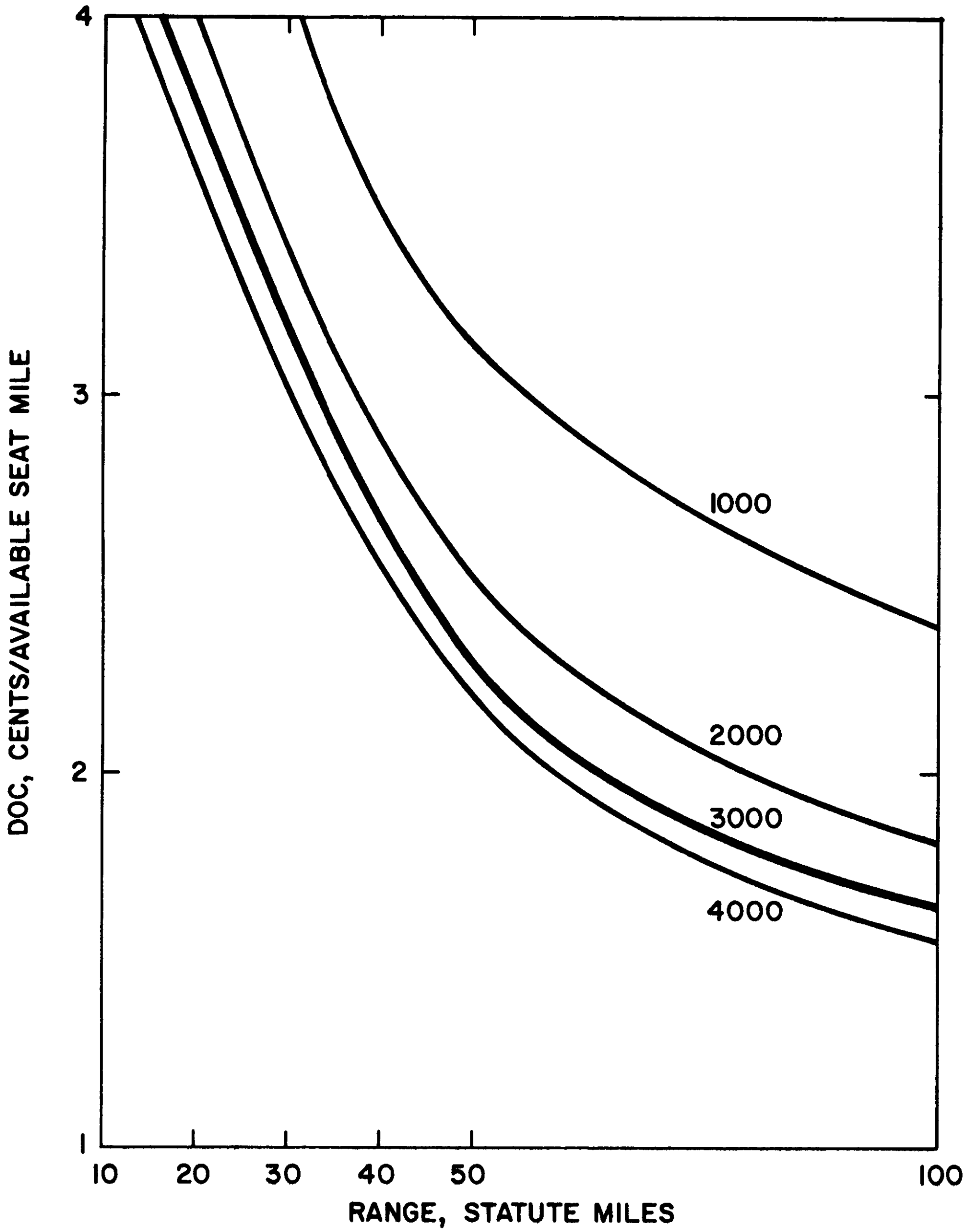

Figure II-37. JET LIFT
ANNUAL UTILIZATION VARIATION (HRS)

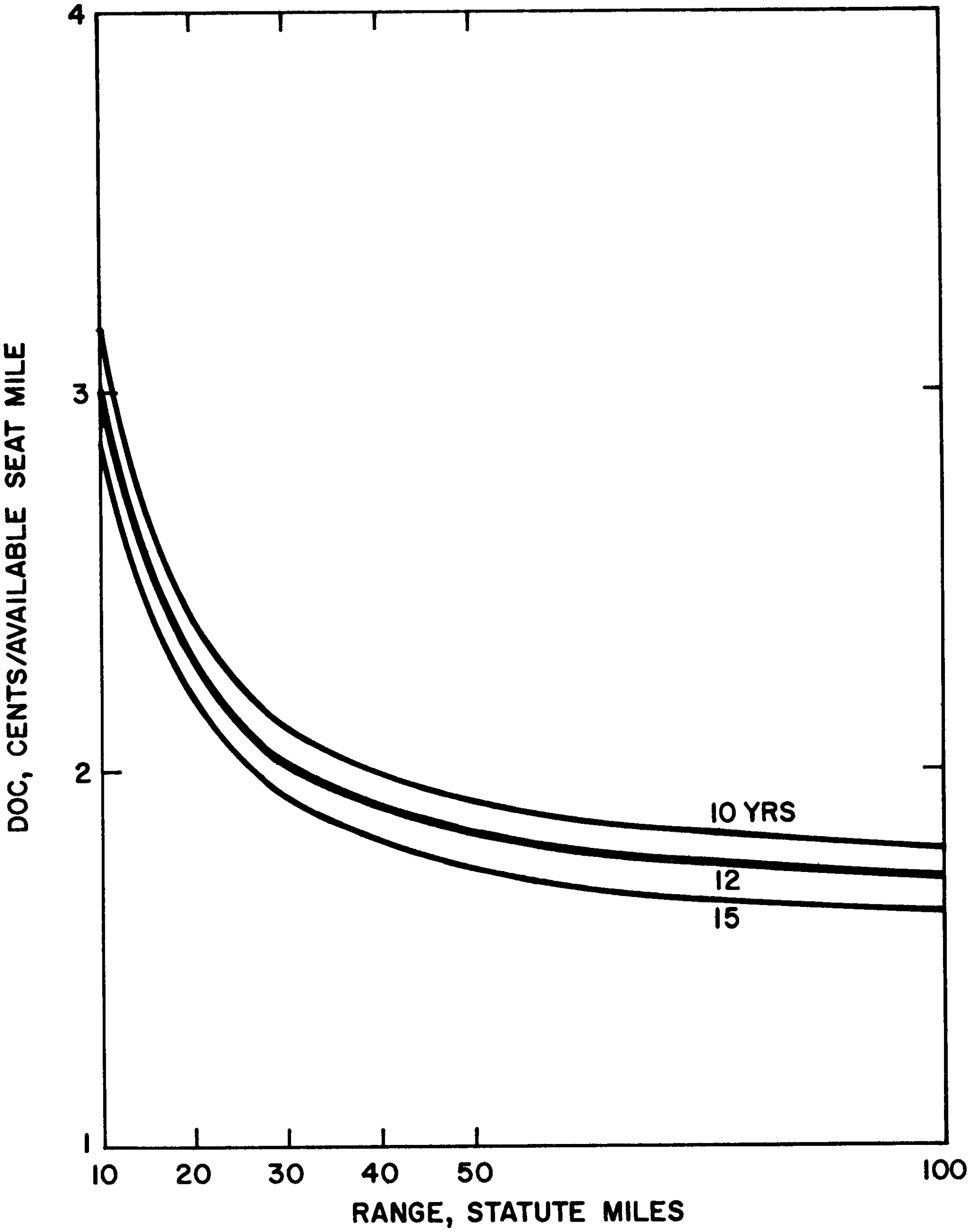

Figure II-38. TILT WING
DEPRECIATION PERIOD VARIATION

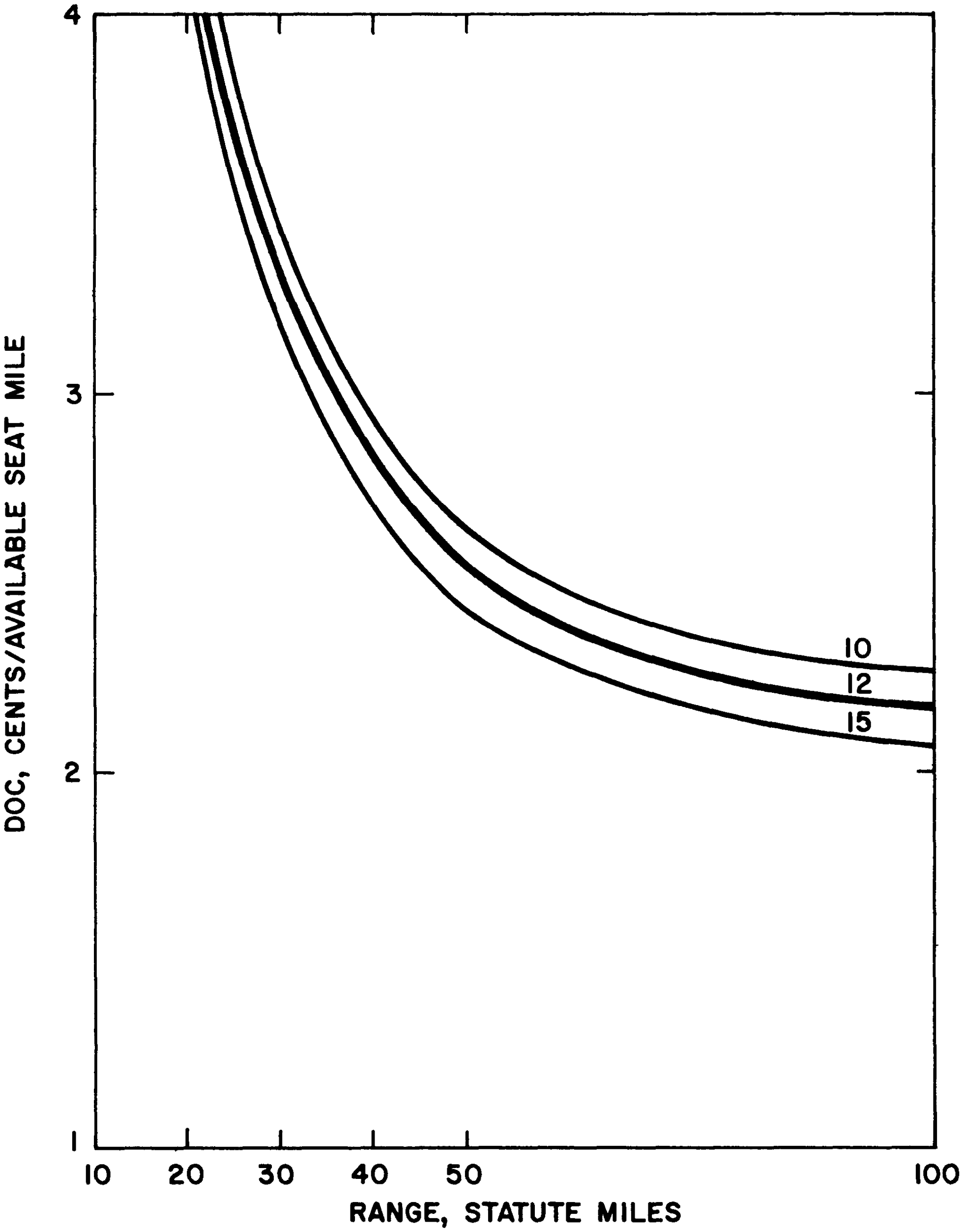

Figure II-39. STOL
DEPRECIATION PERIOD VARIATION (YRS)

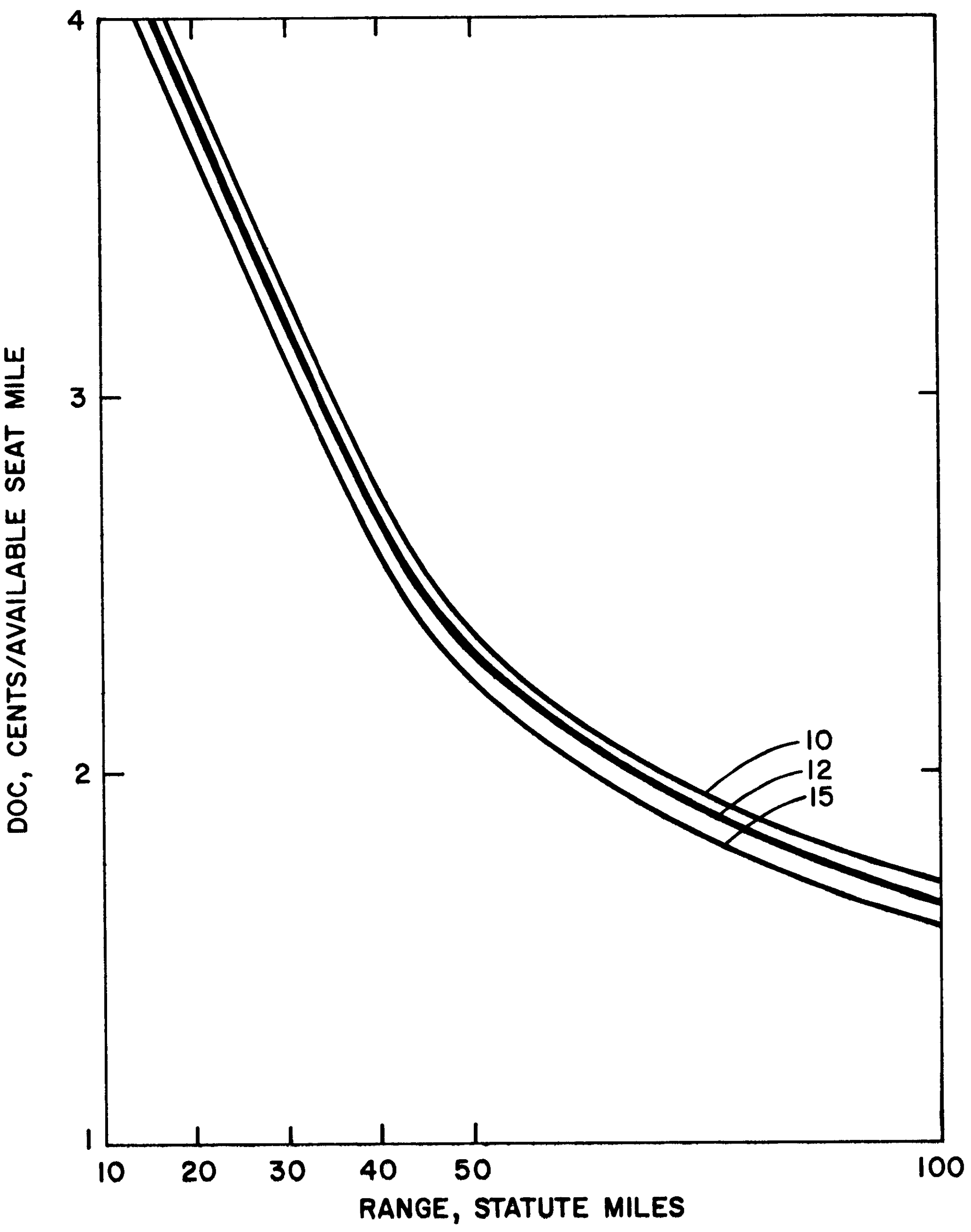

Figure II-40. JET LIFT
DEPRECIATION PERIOD VARIATION (YRS)

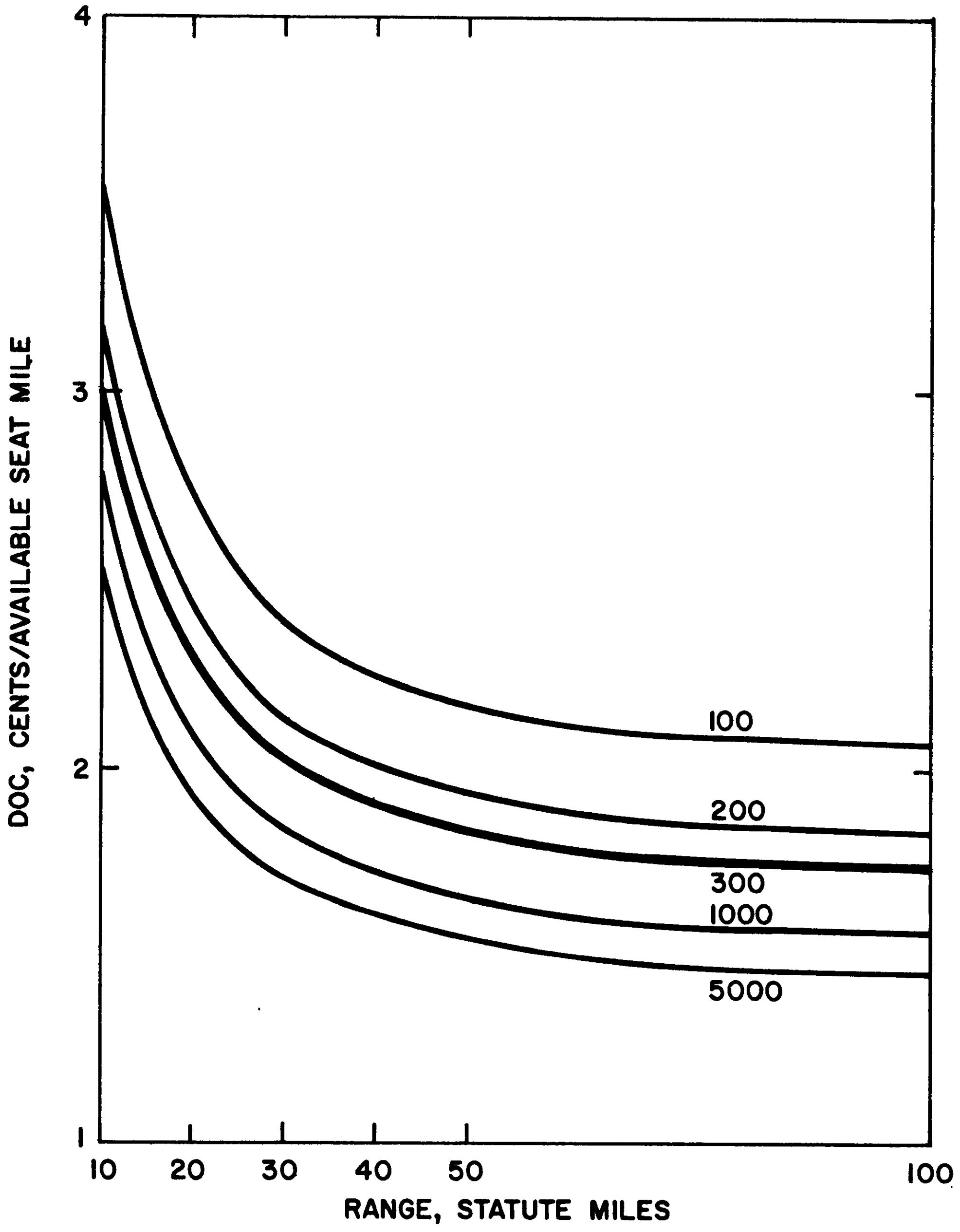

Figure II-41. TILT WING
PRODUCTION RUN VARIATION

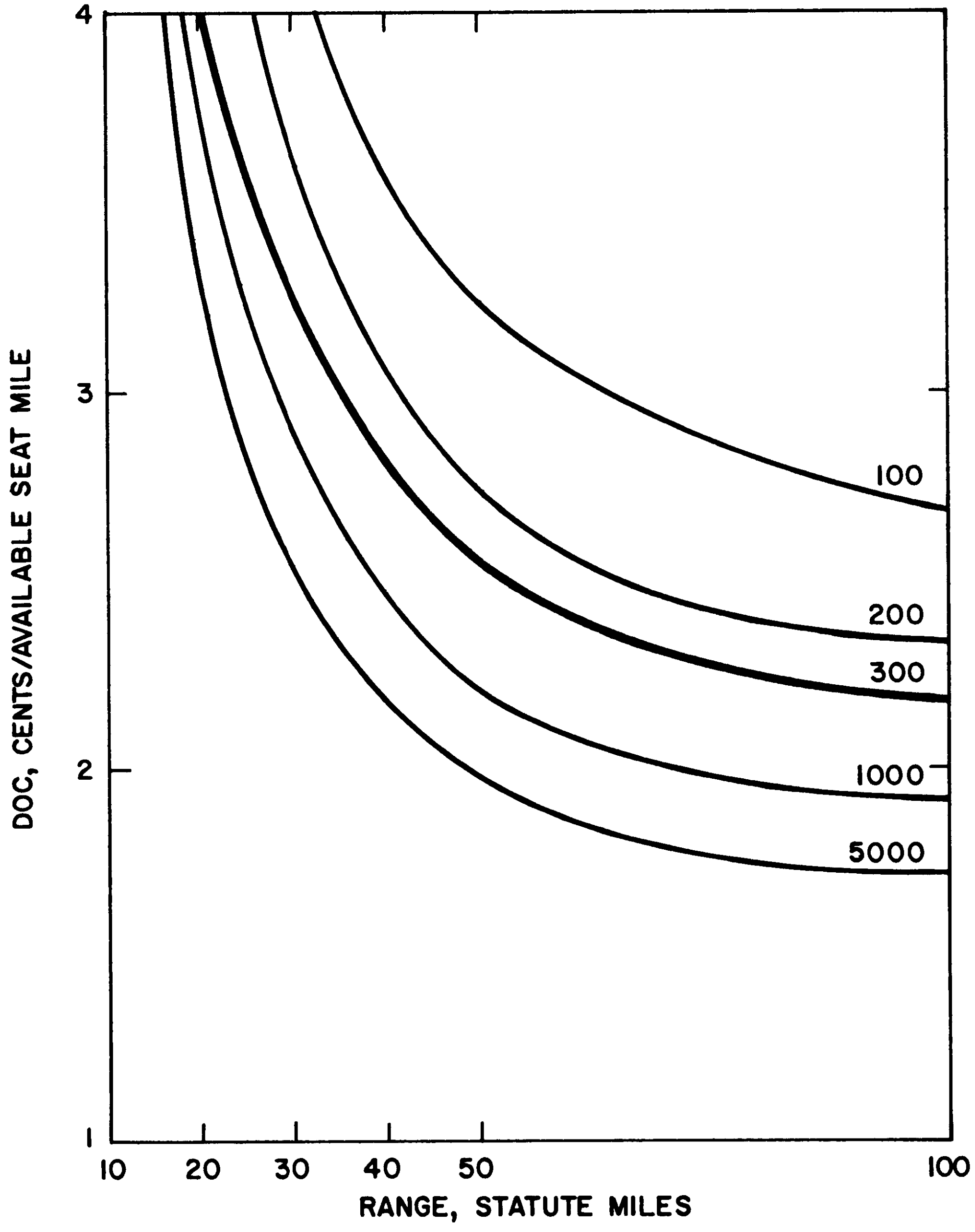

Figure II-42. STOL
PRODUCTION RUN VARIATION

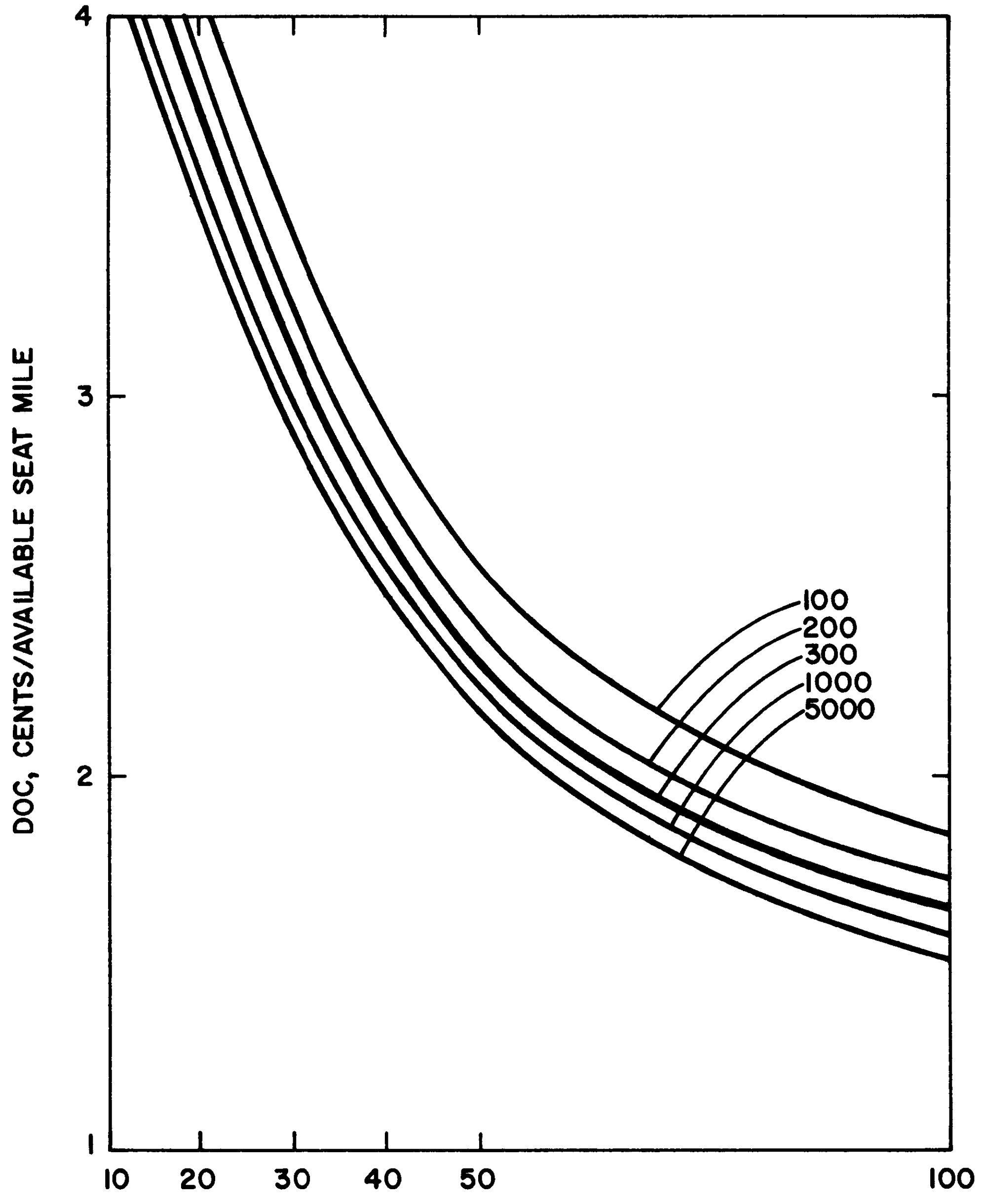

Figure II-43. JET LIFT
PRODUCTION RUN VARIATION

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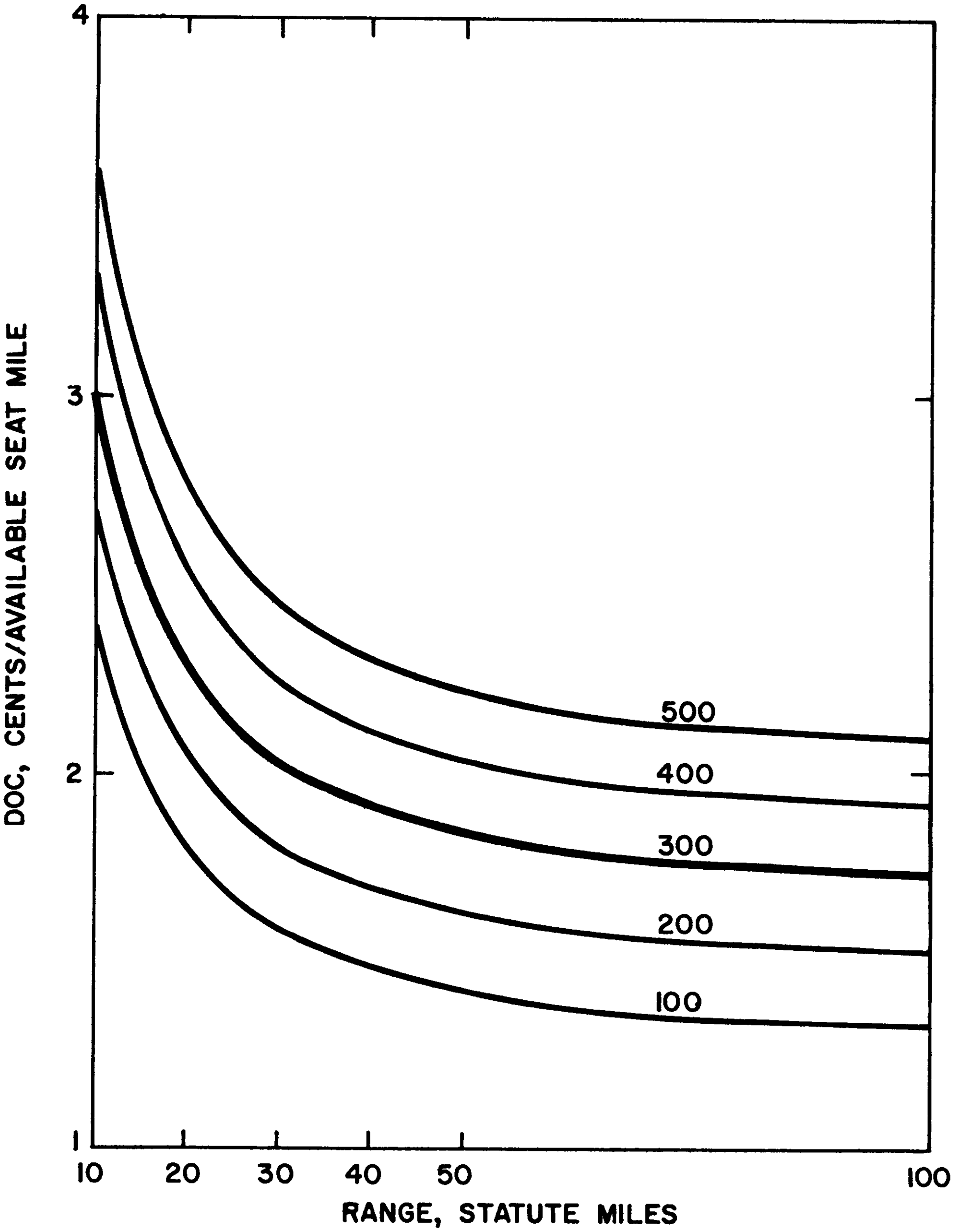

Figure II-44. TILT WING
DOLLARS/LB OF ENGINE VARIATION

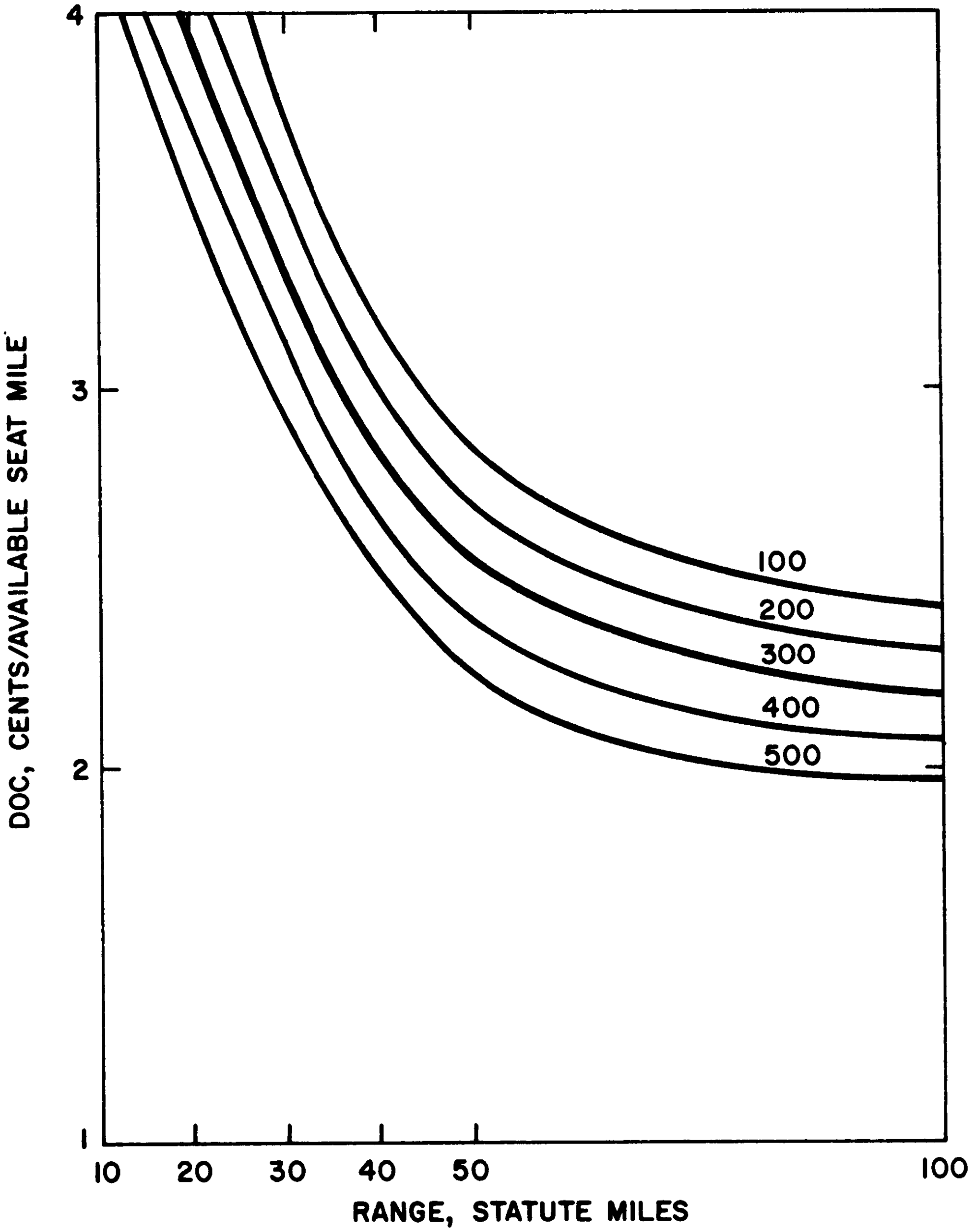

Figure II-45. STOL
DOLLARS/LB OF ENGINE VARIATION

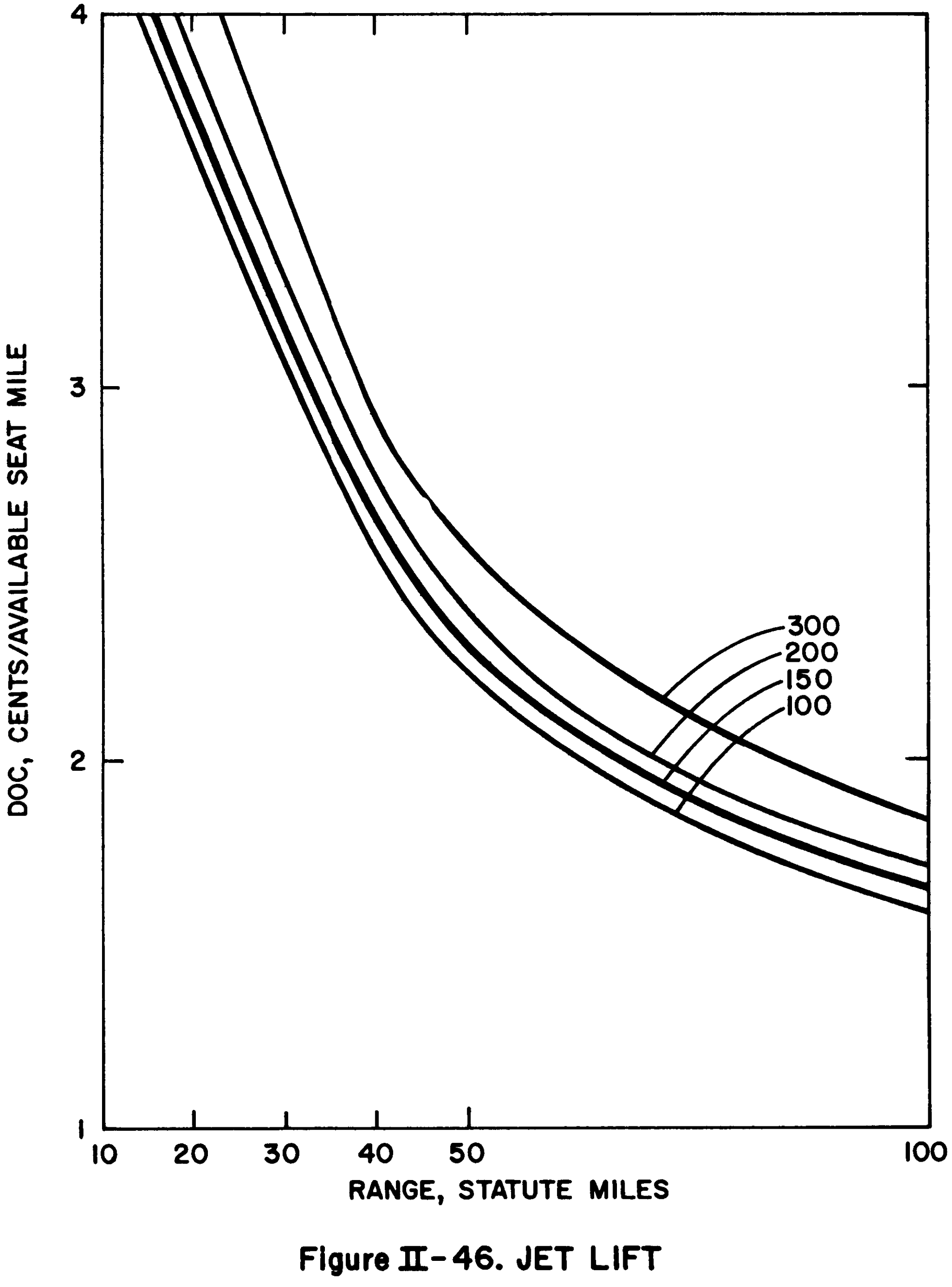

Figure II-46. JET LIFT
DOLLARS/LB OF ENGINE VARIATION

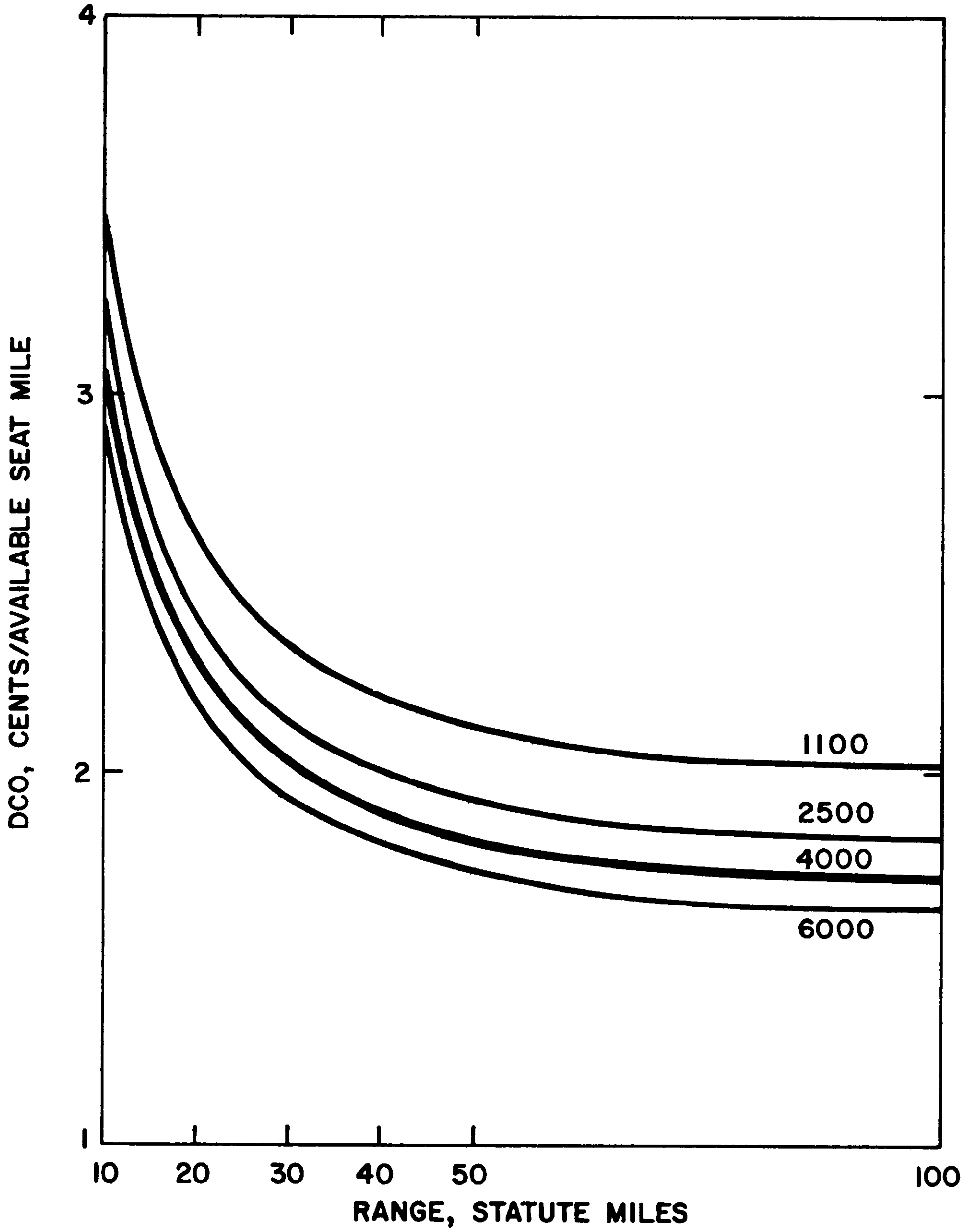

Figure II-47. TILT WING
TIME BETWEEN OVERHAULS ENGINE VARIATION (HRS)

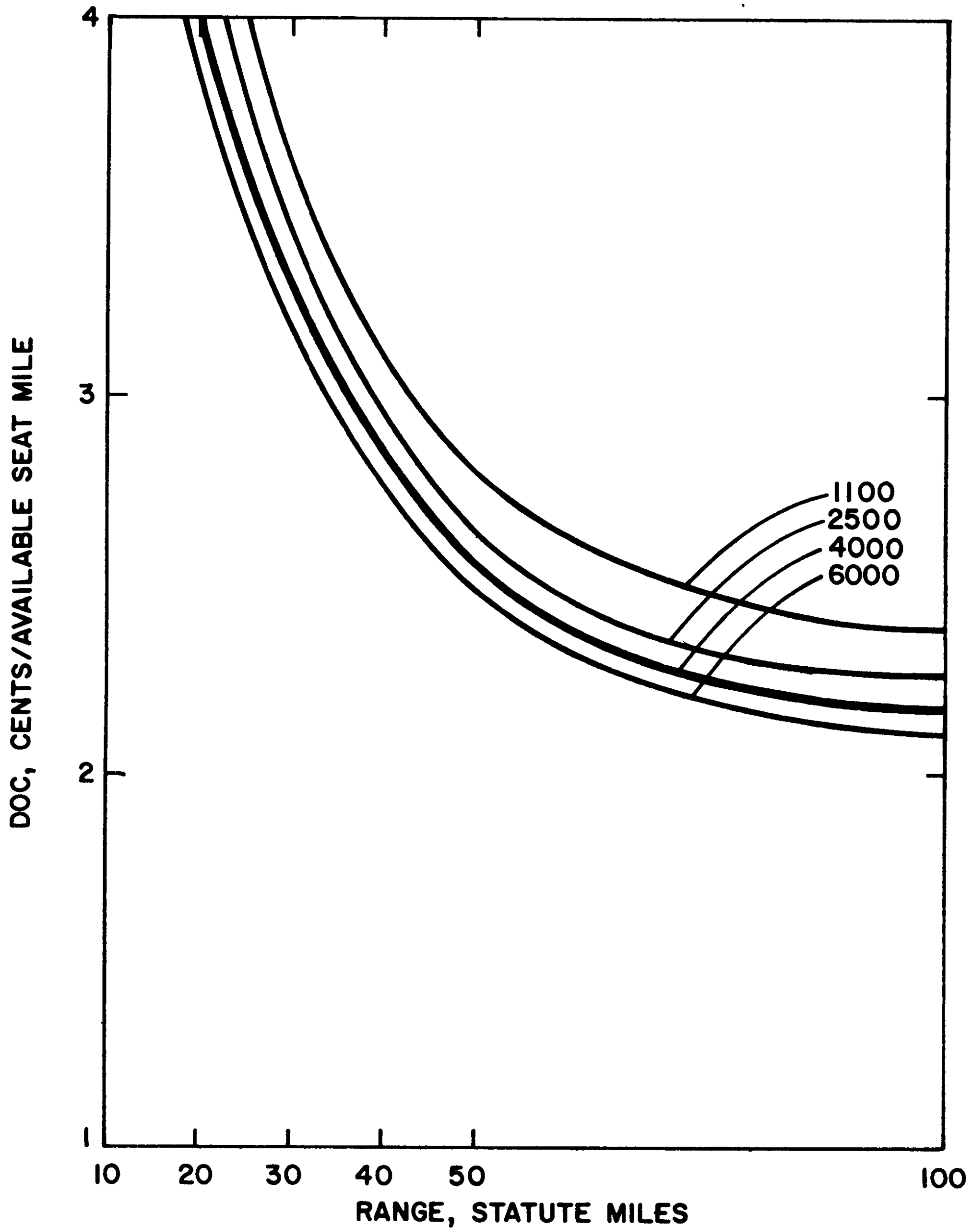

Figure II-48. STOL
TIME BETWEEN OVERHAUL OF ENGINES VARIATION (HRS)

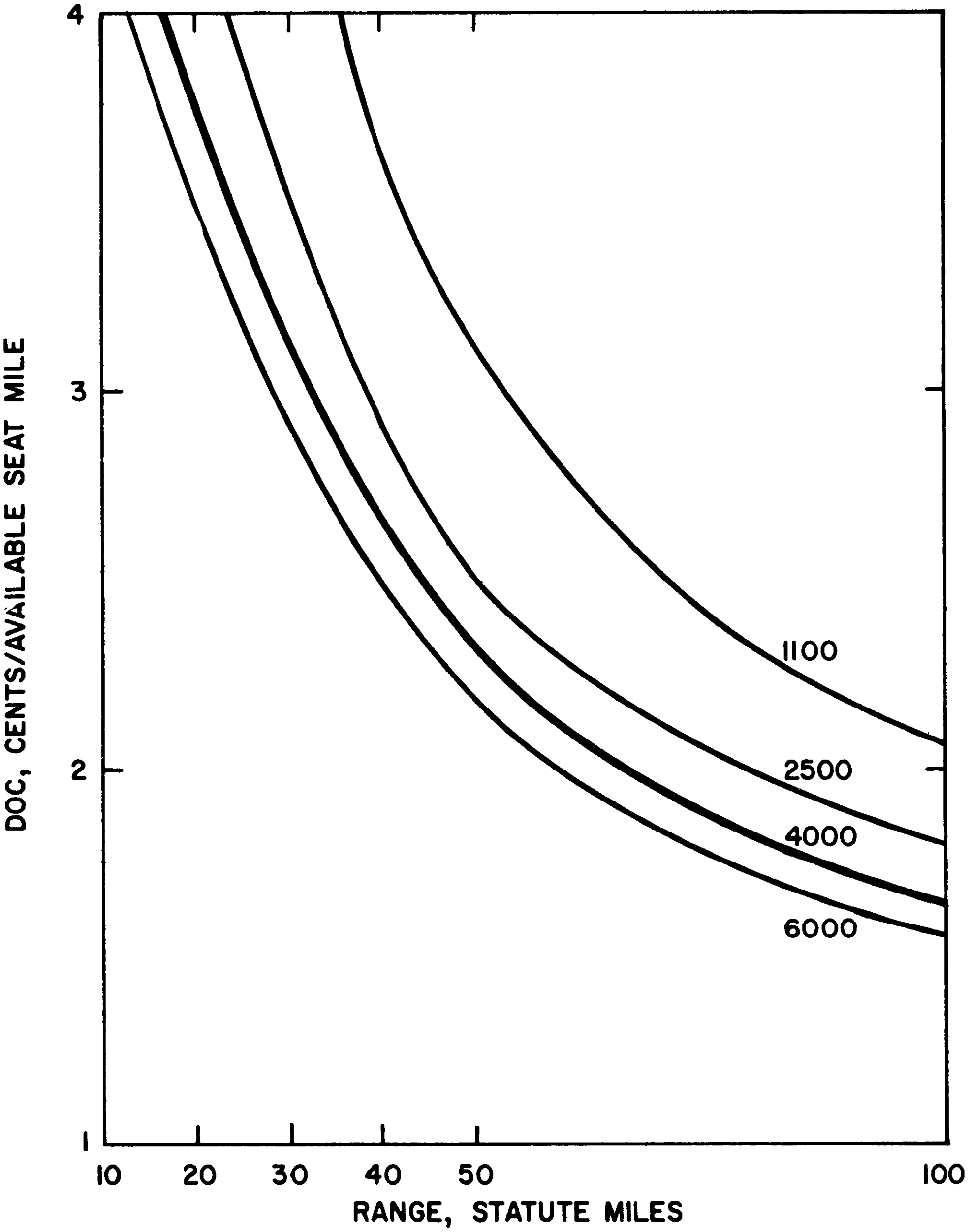

Figure II-49. JET LIFT
TIME BETWEEN OVERHAUL OF ENGINES VARIATION (HRS)

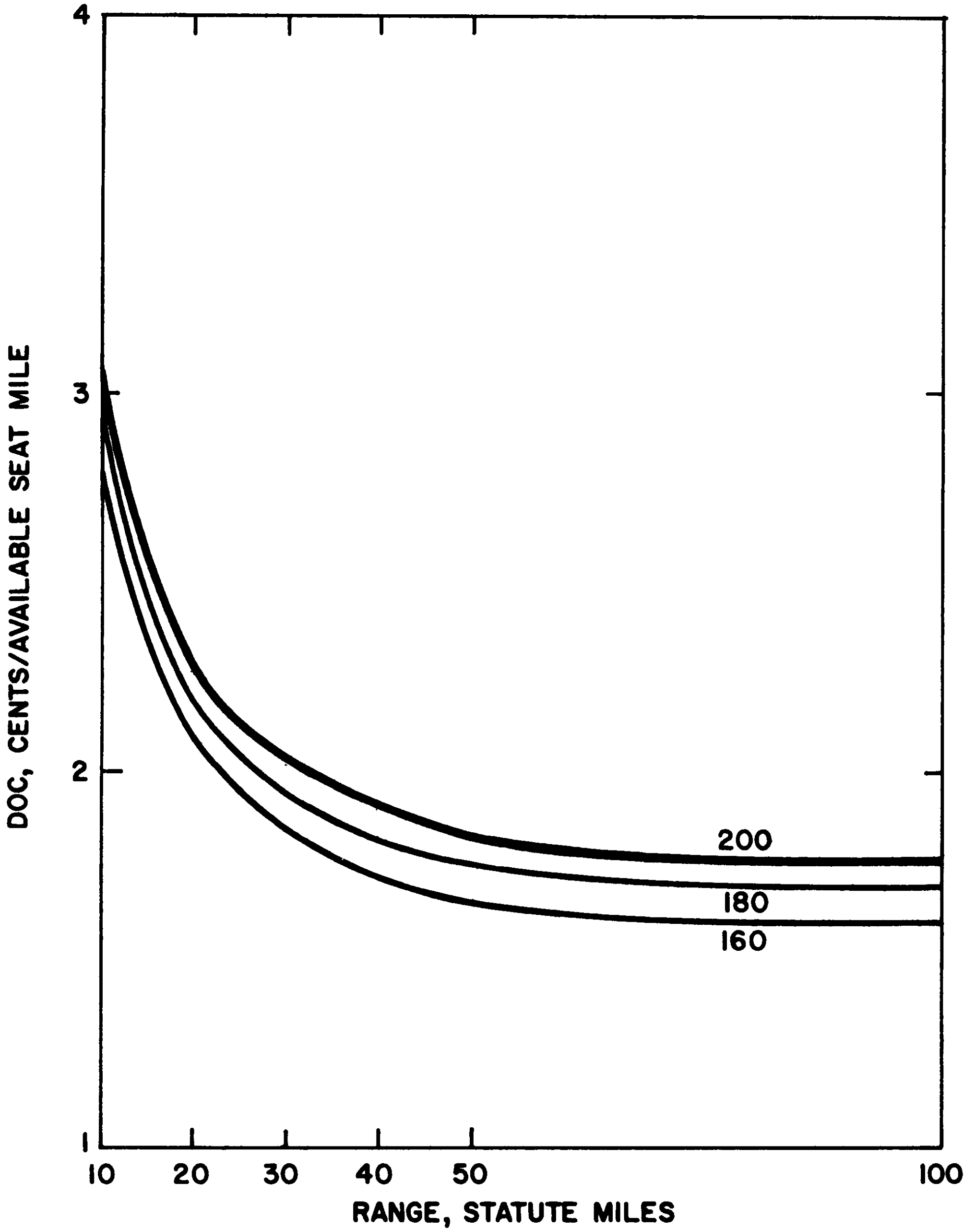

Figure II-50. TILT WING
WEIGHT/PASSENGER VARIATION (LB/PASS.)

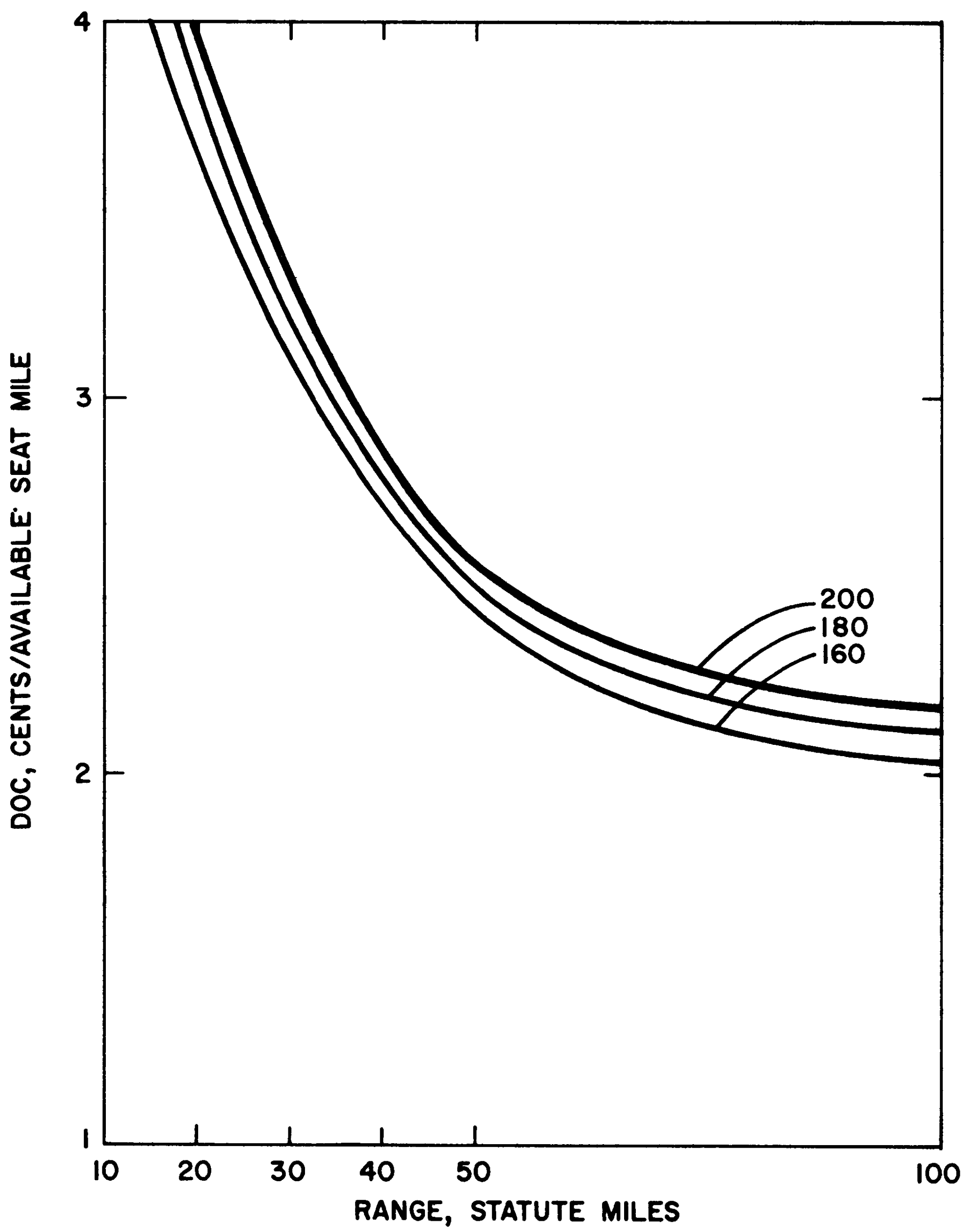

Figure II-51. STOL
WEIGHT/PASSENGER VARIATION (LB/PASS.)

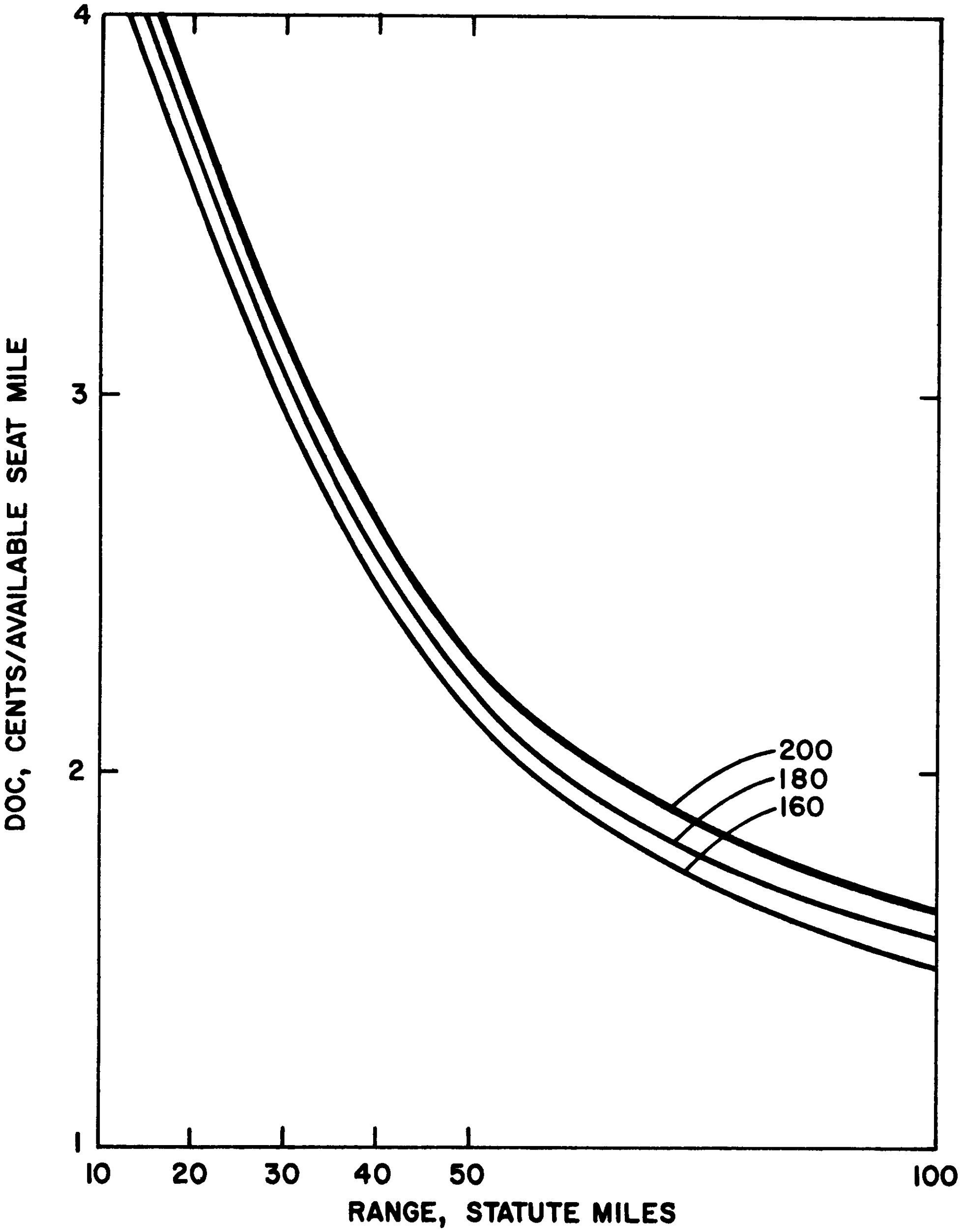

Figure II-52. JET LIFT
WEIGHT/PASSENGER VARIATION (LB/PASS.)

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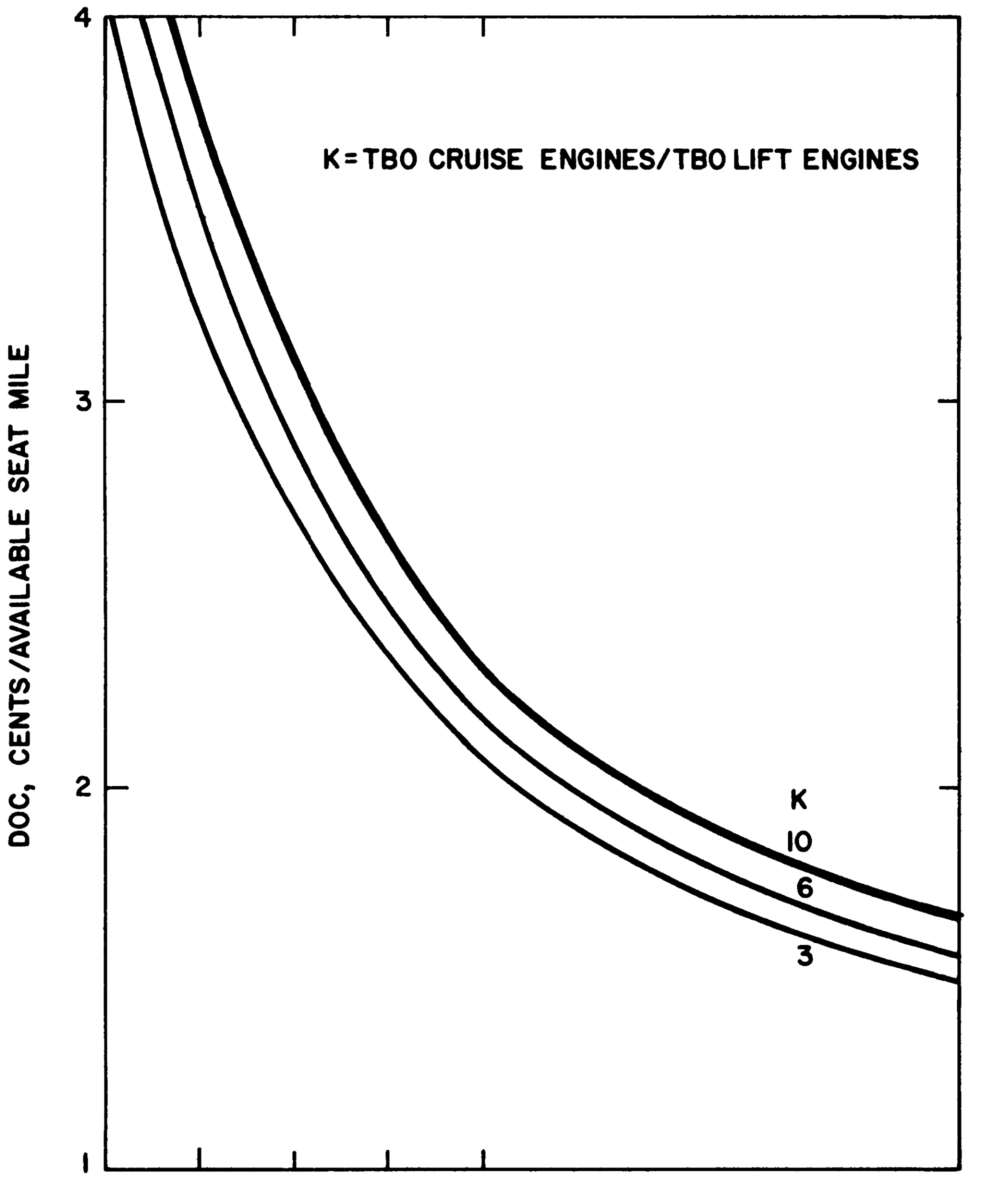


Figure II-53. JET LIFT
VARIATION OF TIME BETWEEN OVERHAUL OF LIFT ENGINES (TBO)

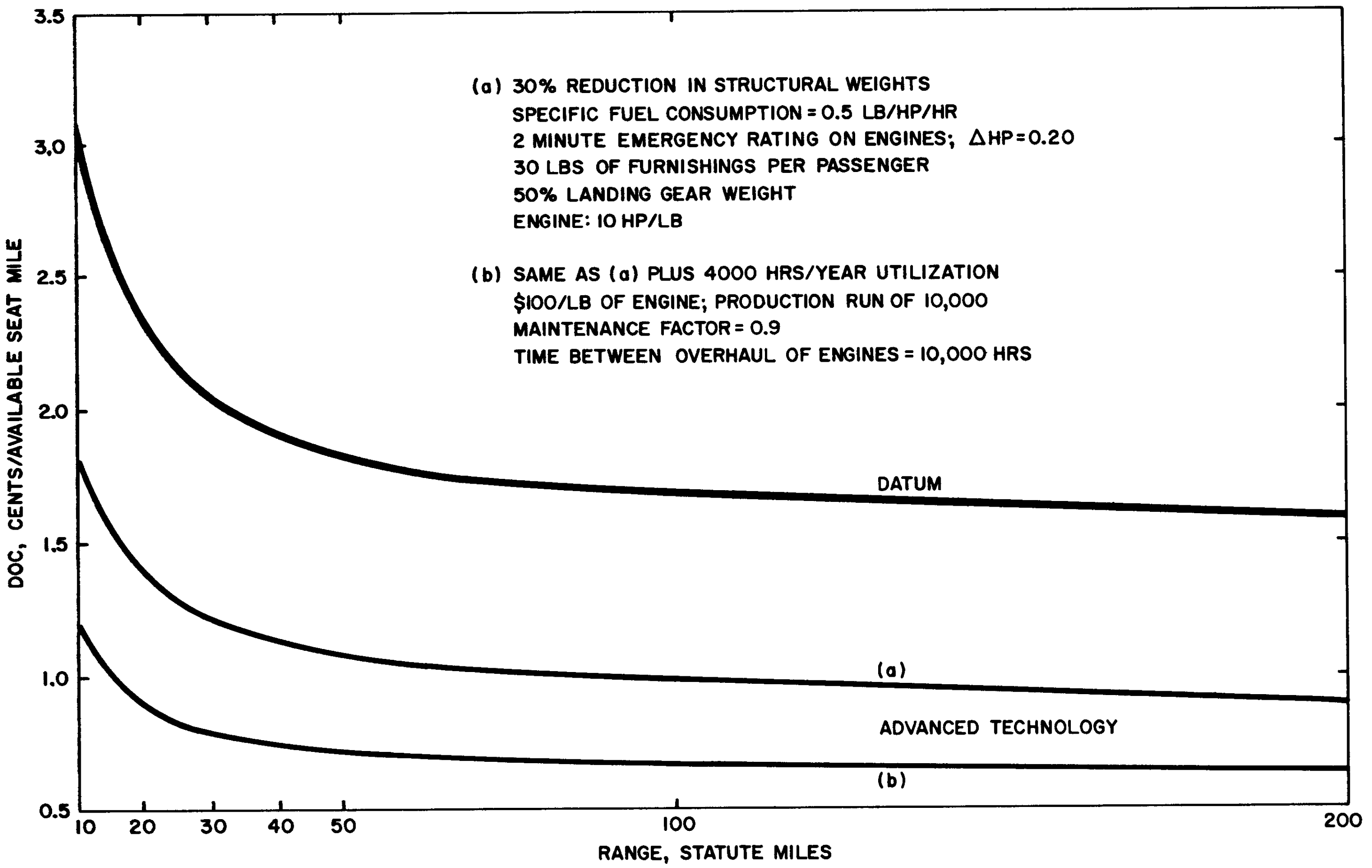


Figure II-54. ADVANCED TECHNOLOGY TILT WING

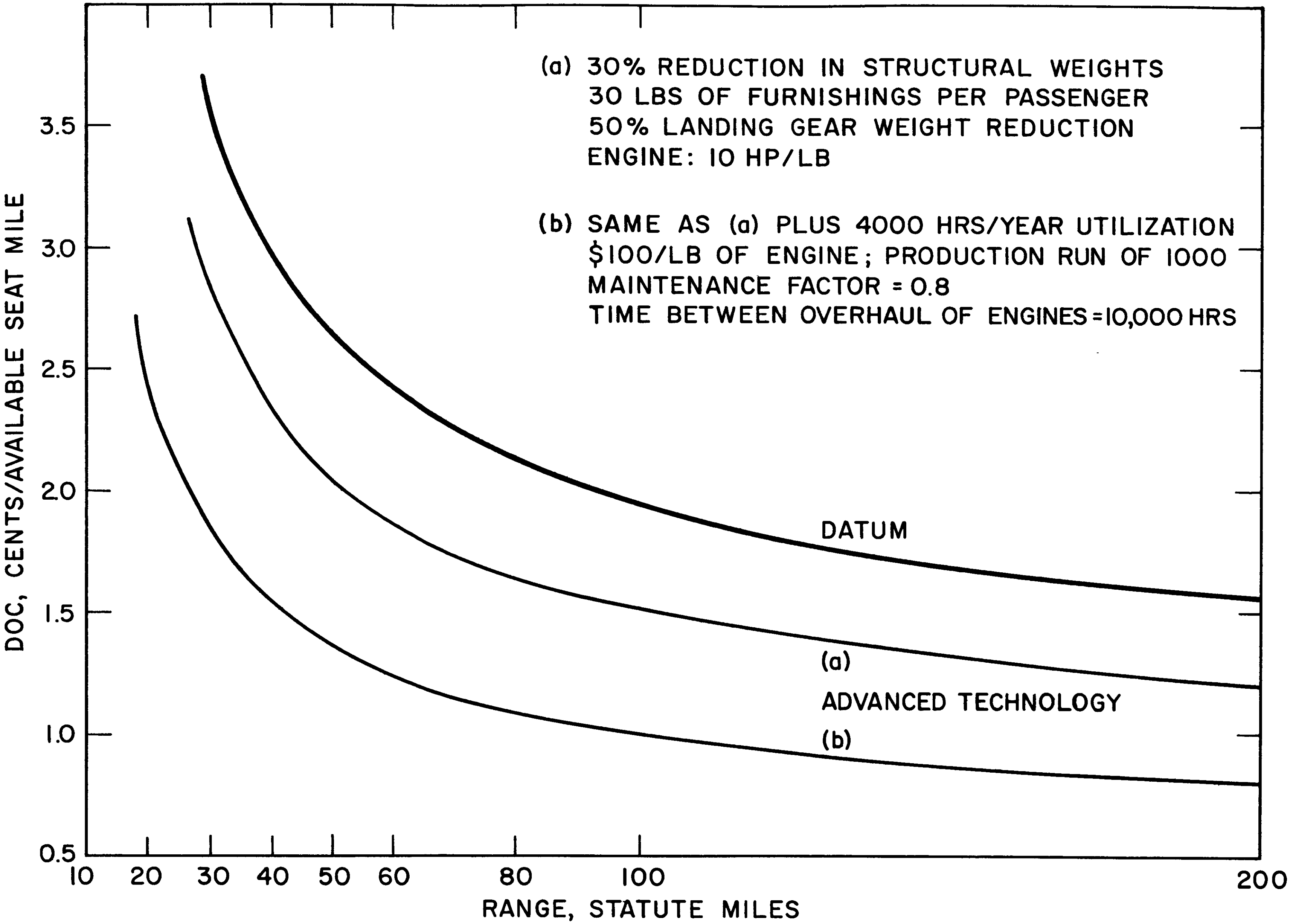


Figure II-55. ADVANCED TECHNOLOGY STOL

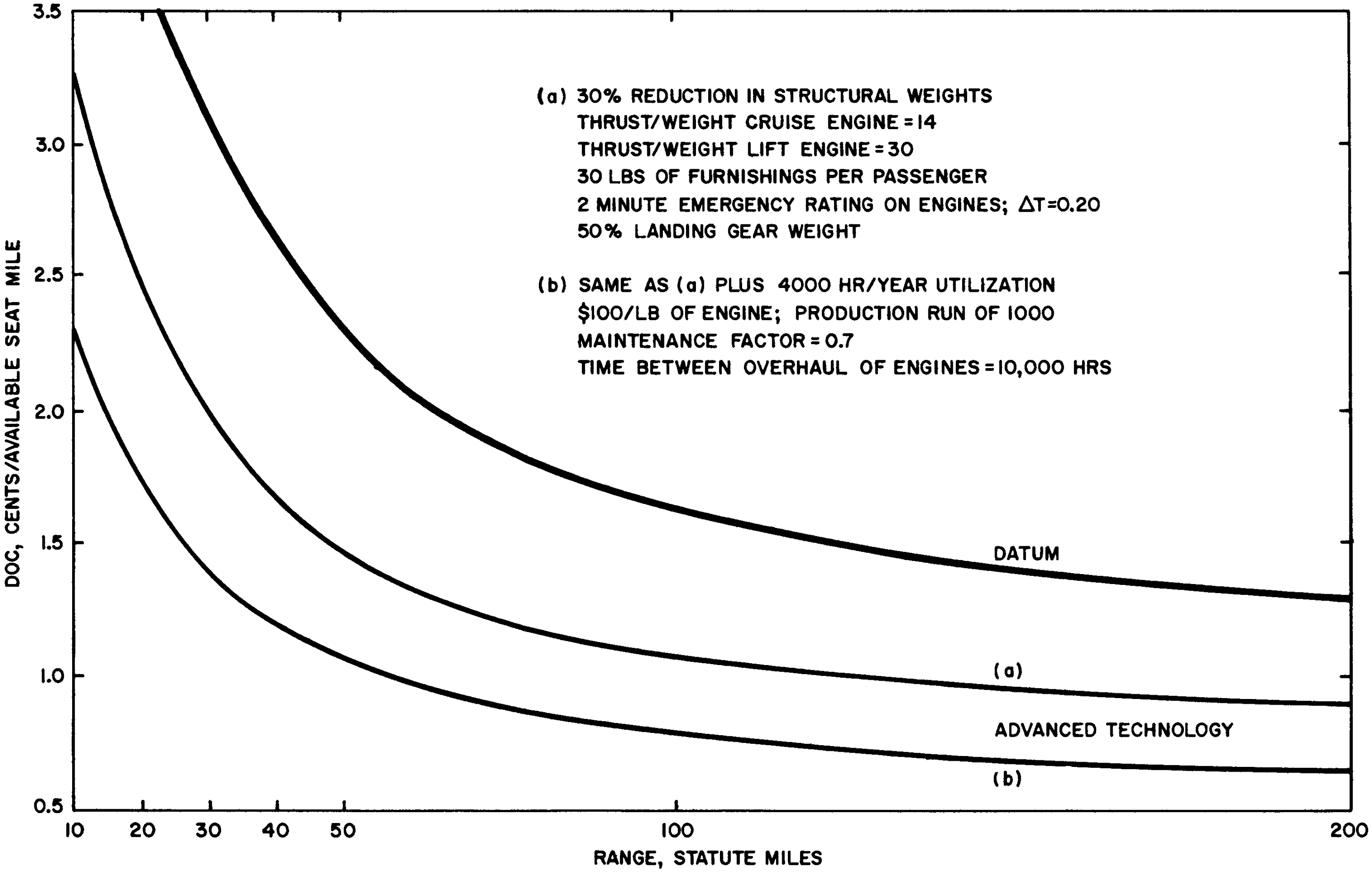


Figure II-56. ADVANCED TECHNOLOGY JET LIFT

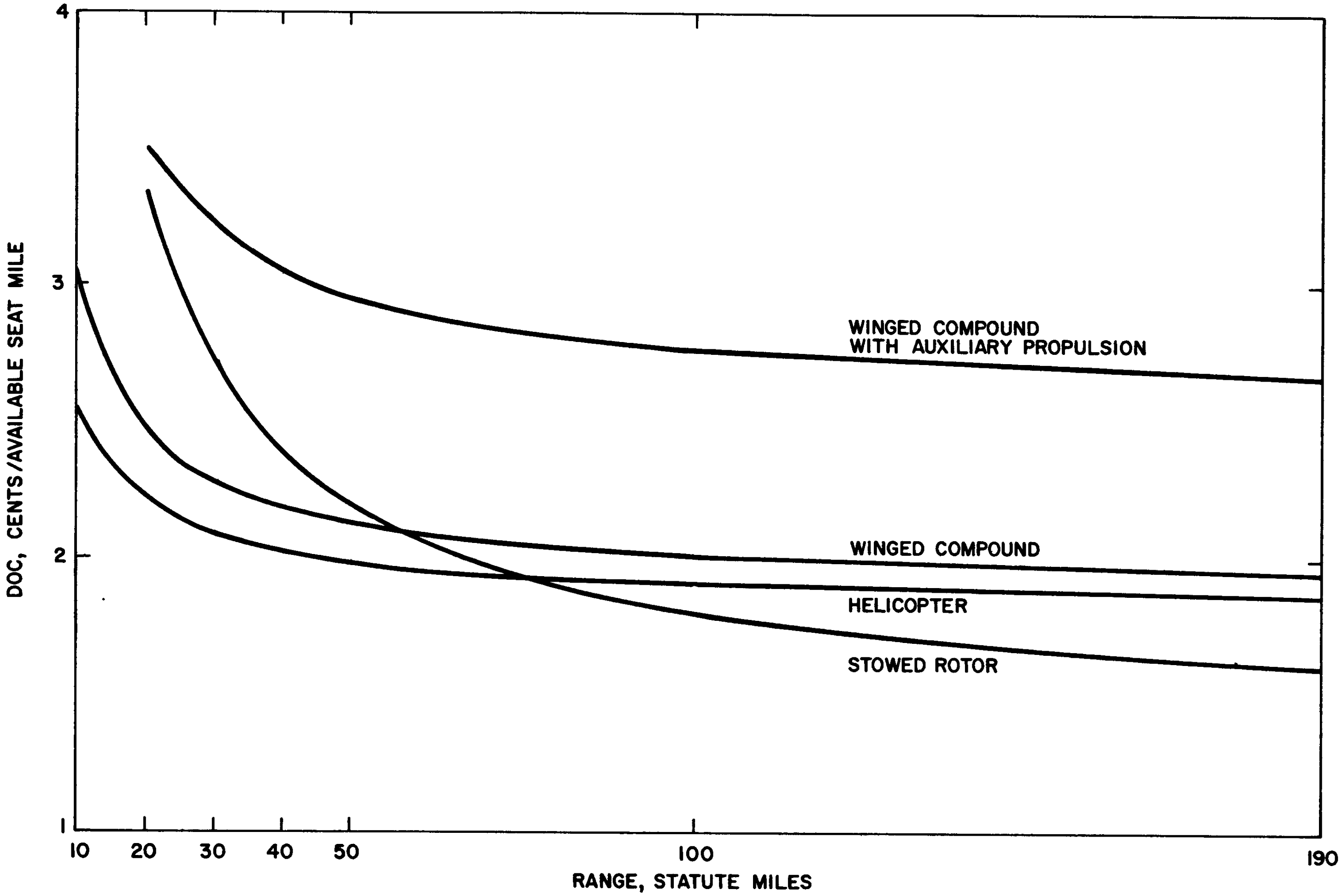


Figure II-57. COMPARATIVE ROTARY WING AIRCRAFT

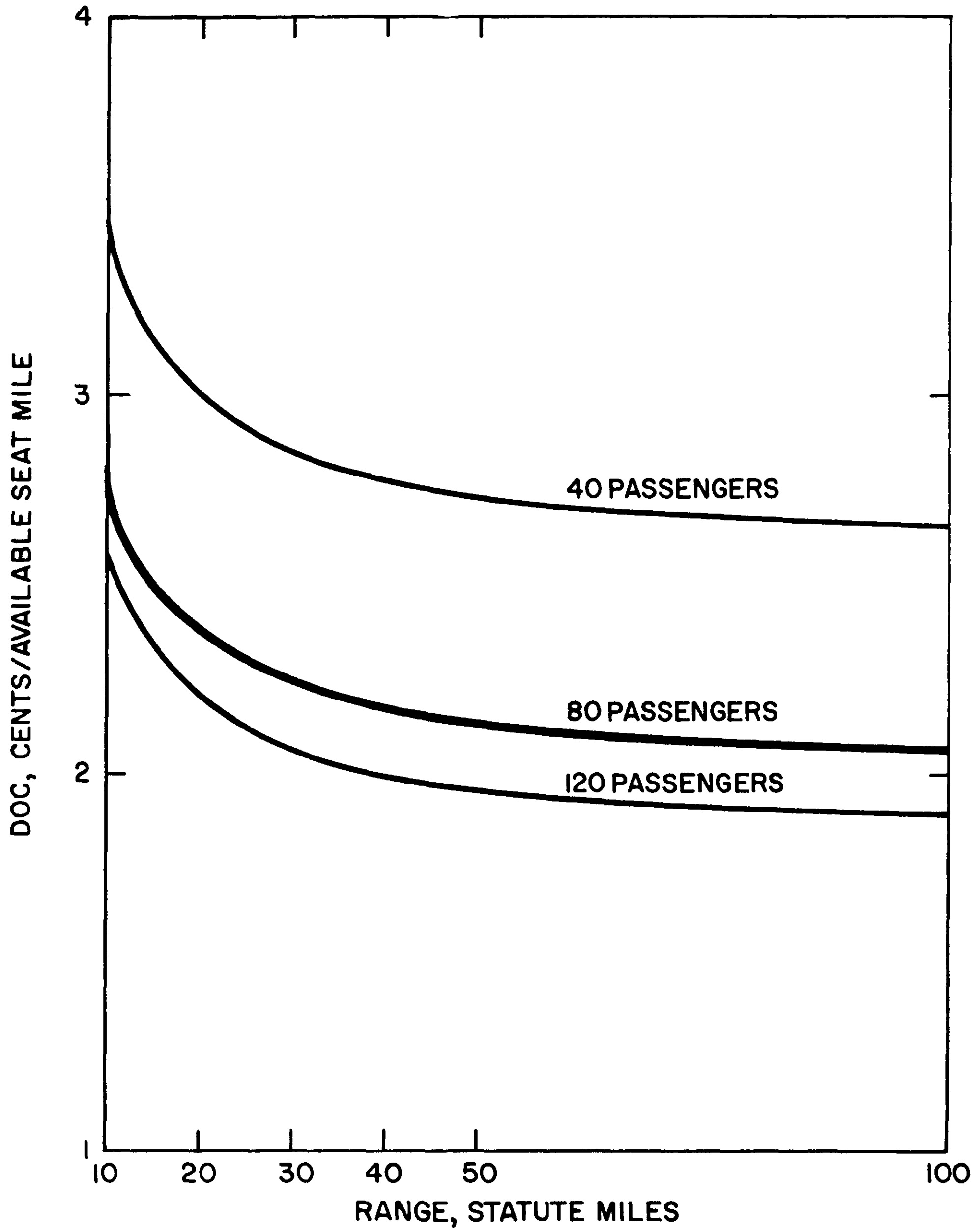


Figure II-58. HELICOPTER
NUMBER OF PASSENGERS VARIATION

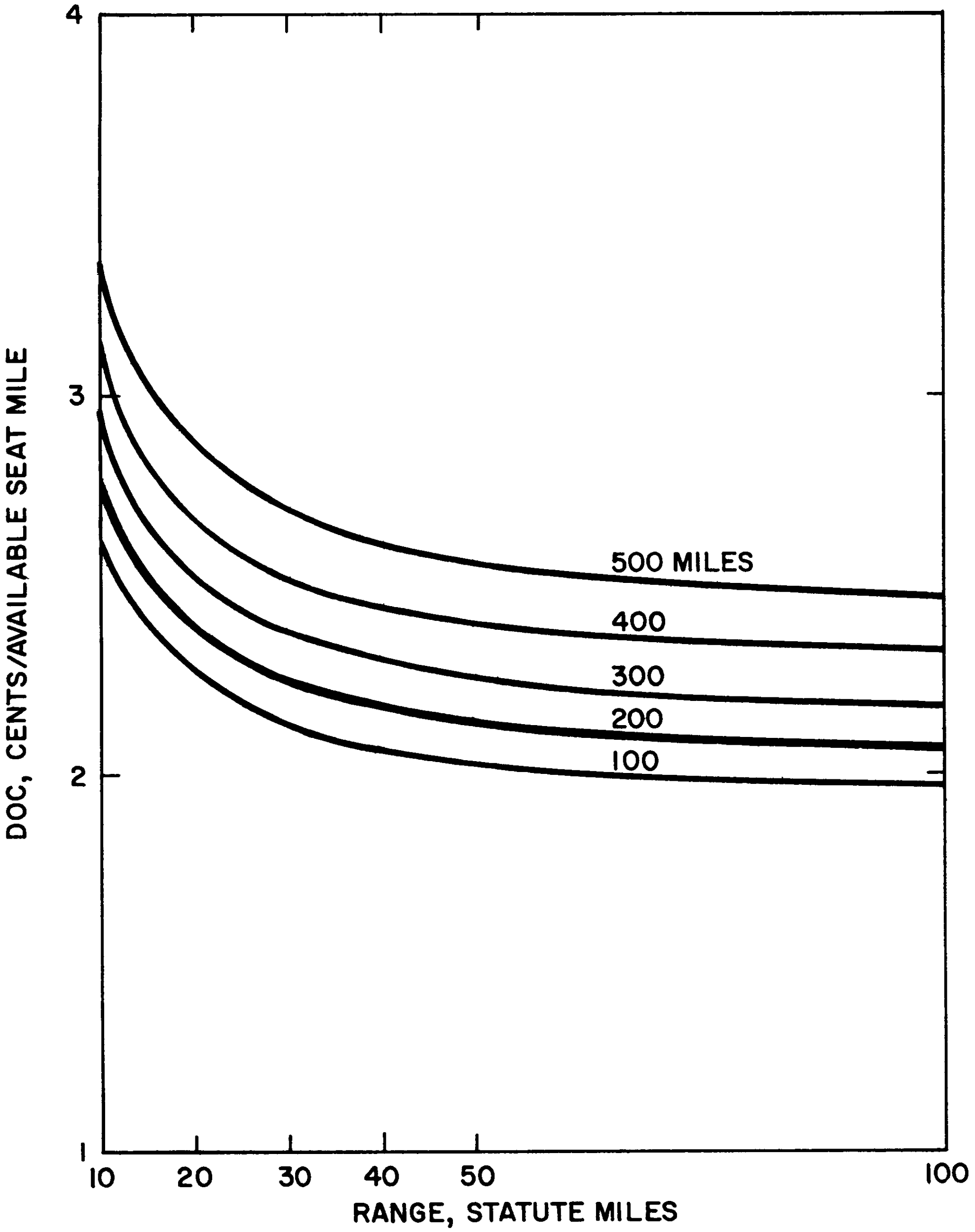


Figure II-59. HELICOPTER
DESIGN RANGE VARIATION (STATUTE MILES)

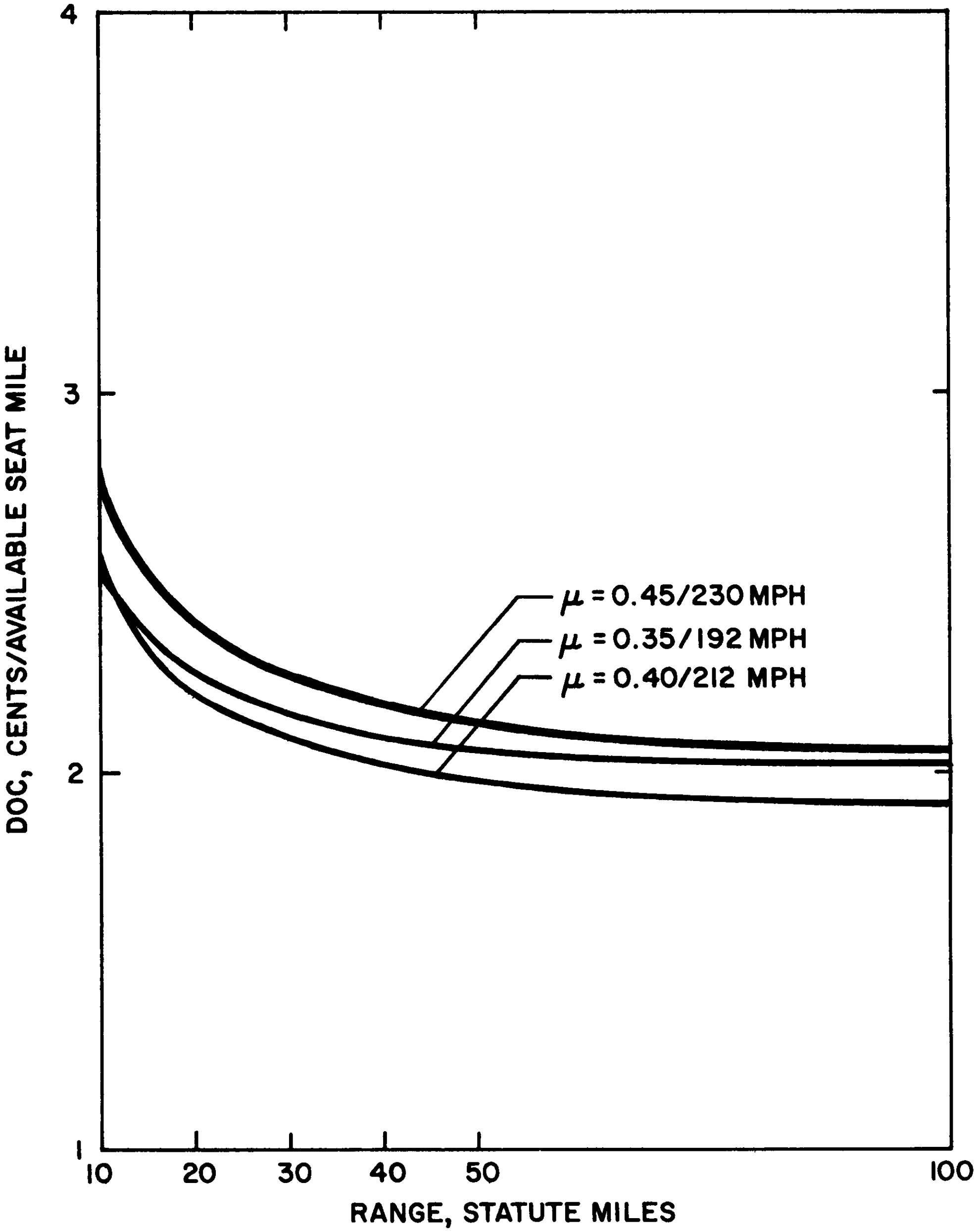


Figure II-60. HELICOPTER
ADVANCED RATIO (μ) IN CRUISE/CRUISE SPEED (MPH) VARIATION

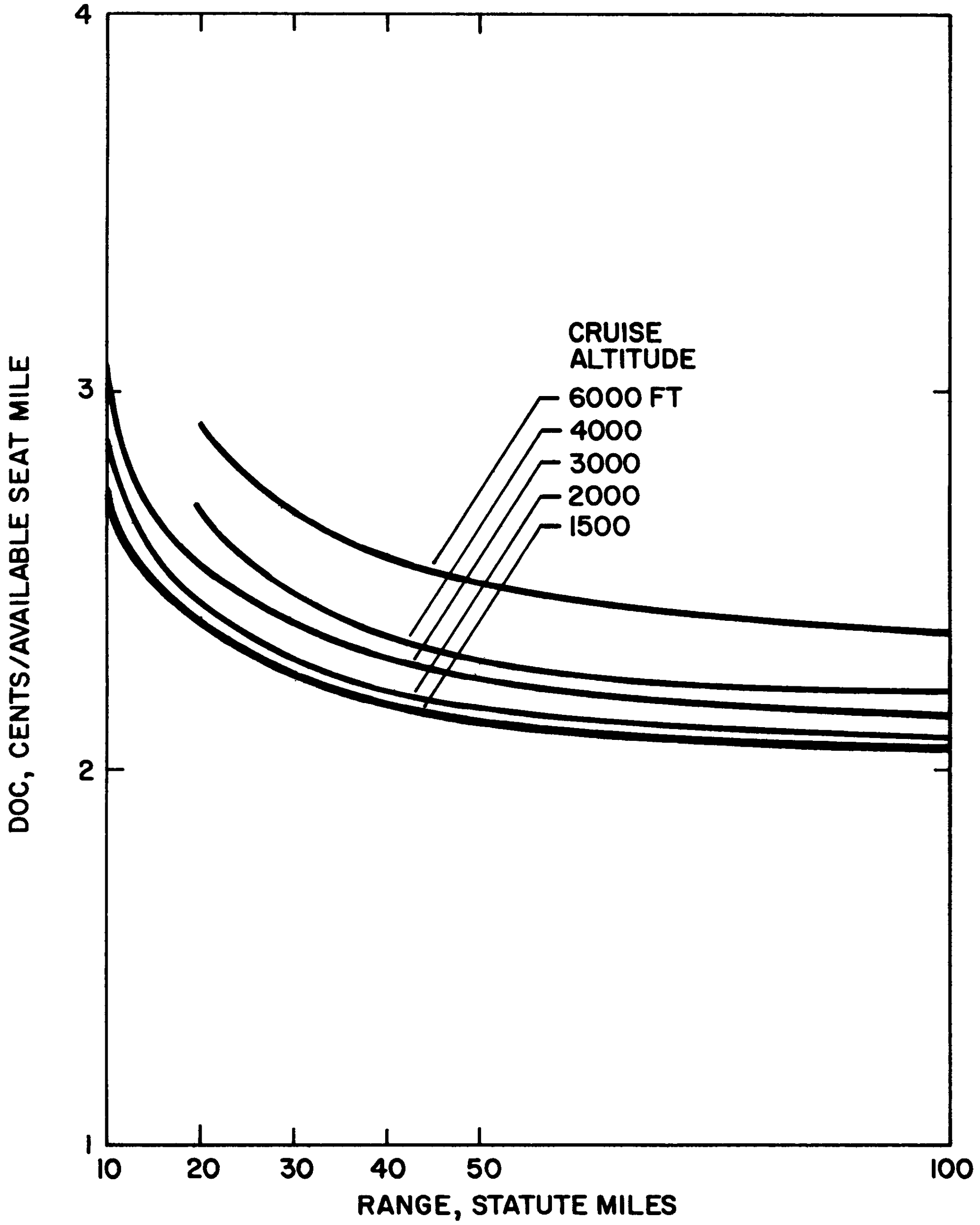


Figure II-61. HELICOPTER
CRUISE ALTITUDE VARIATION (FT)

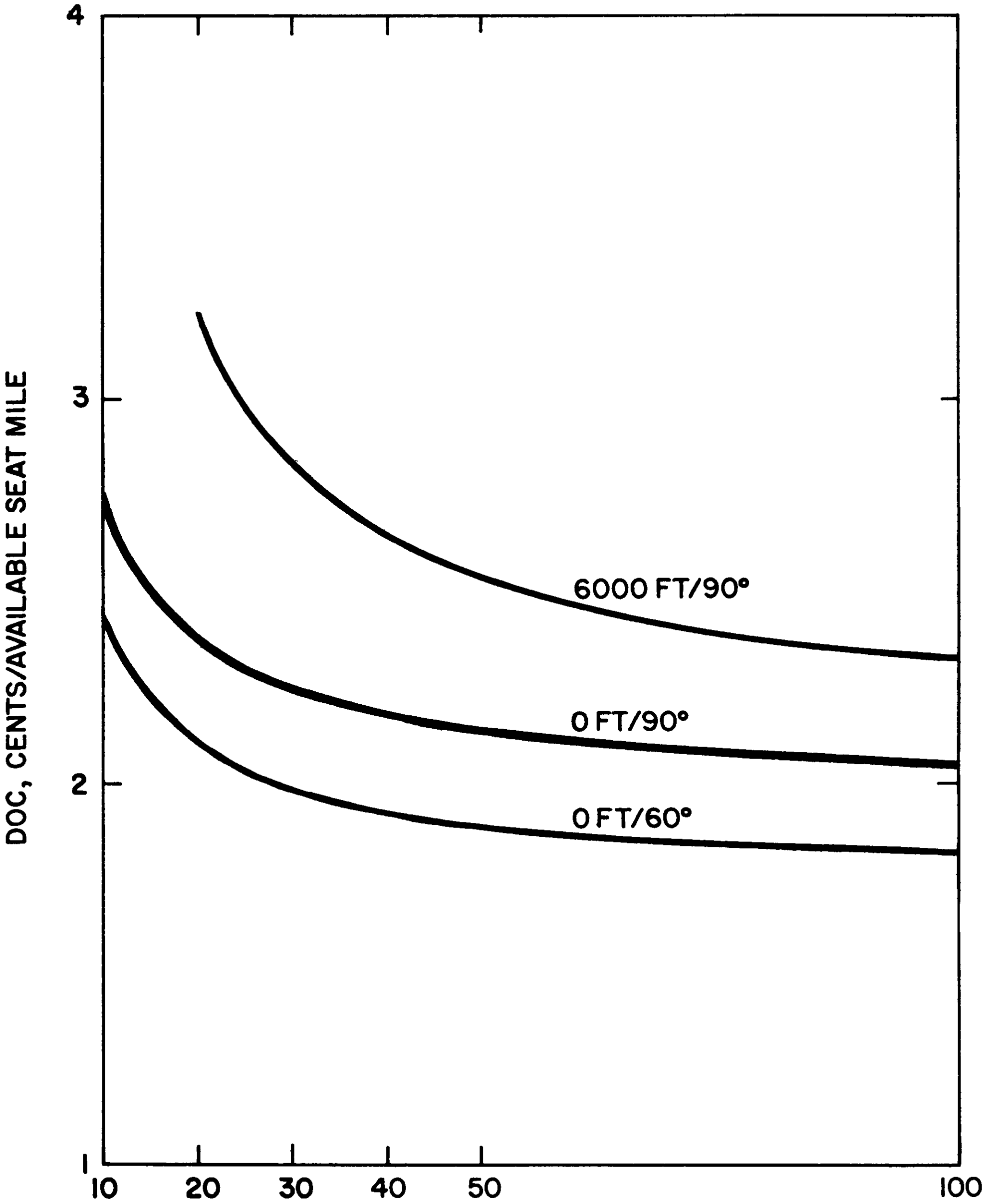


Figure II-62. HELICOPTER
HOVER ALTITUDE (FT)/SEA LEVEL TEMPERATURE (°F) VARIATION

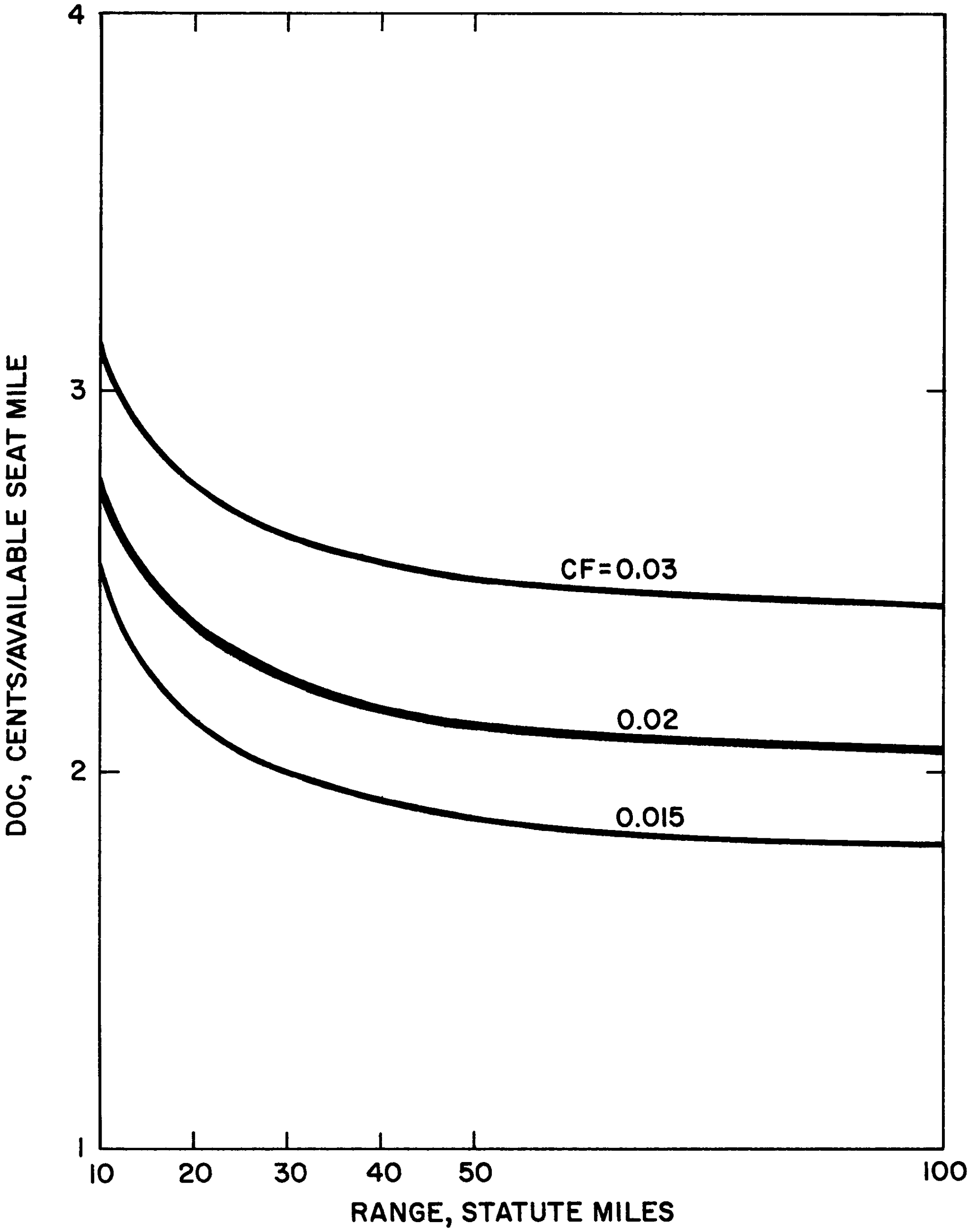


Figure II-63. HELICOPTER
PARASITIC DRAG FACTOR (CF) VARIATION
F = CF (GROSS WEIGHT)$^{2/3}$

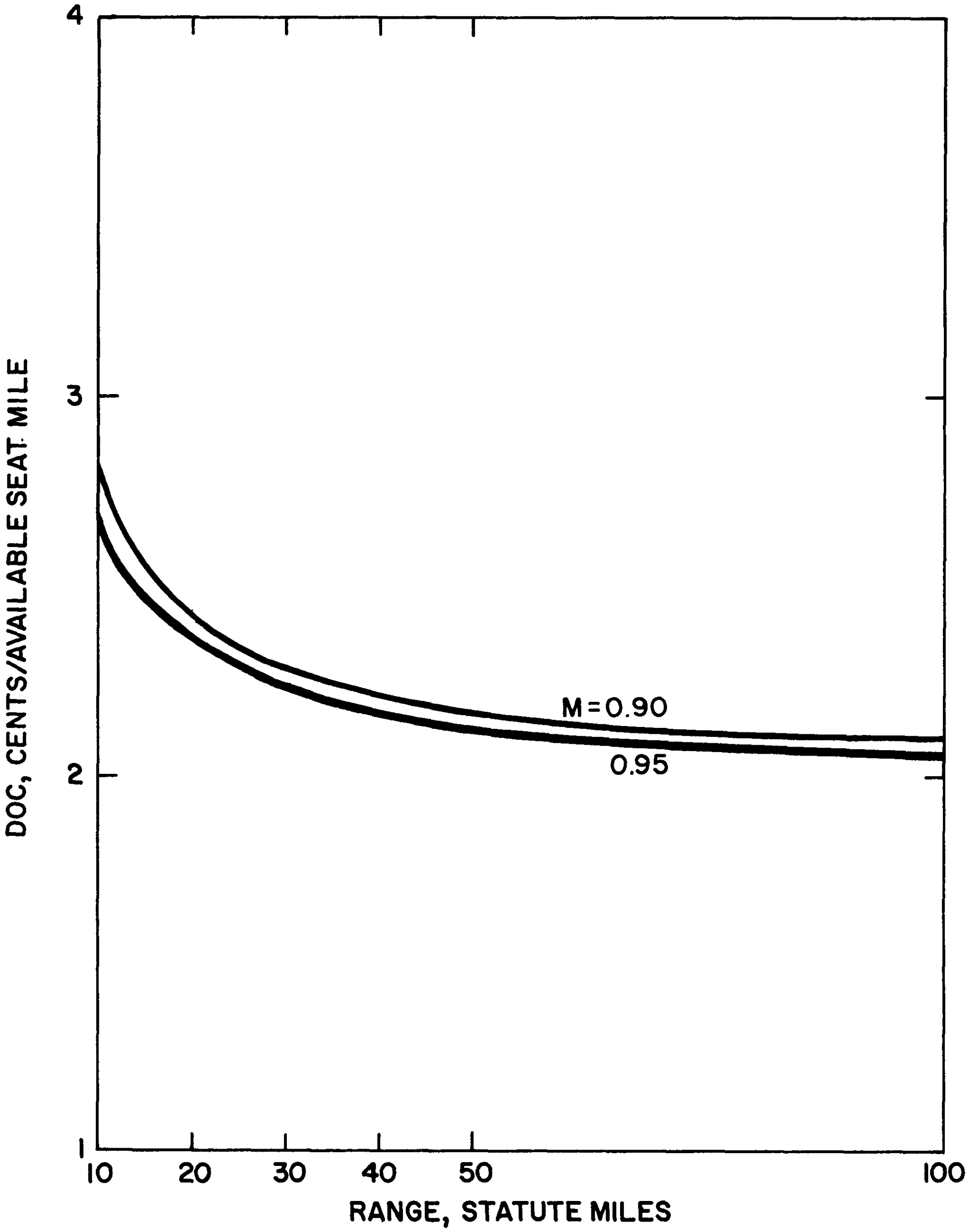


Figure II-64. HELICOPTER
VARIATION WITH MAXIMUM TIP MACH NUMBER FOR NO COMPRESSIBILITY LOSSES (M)

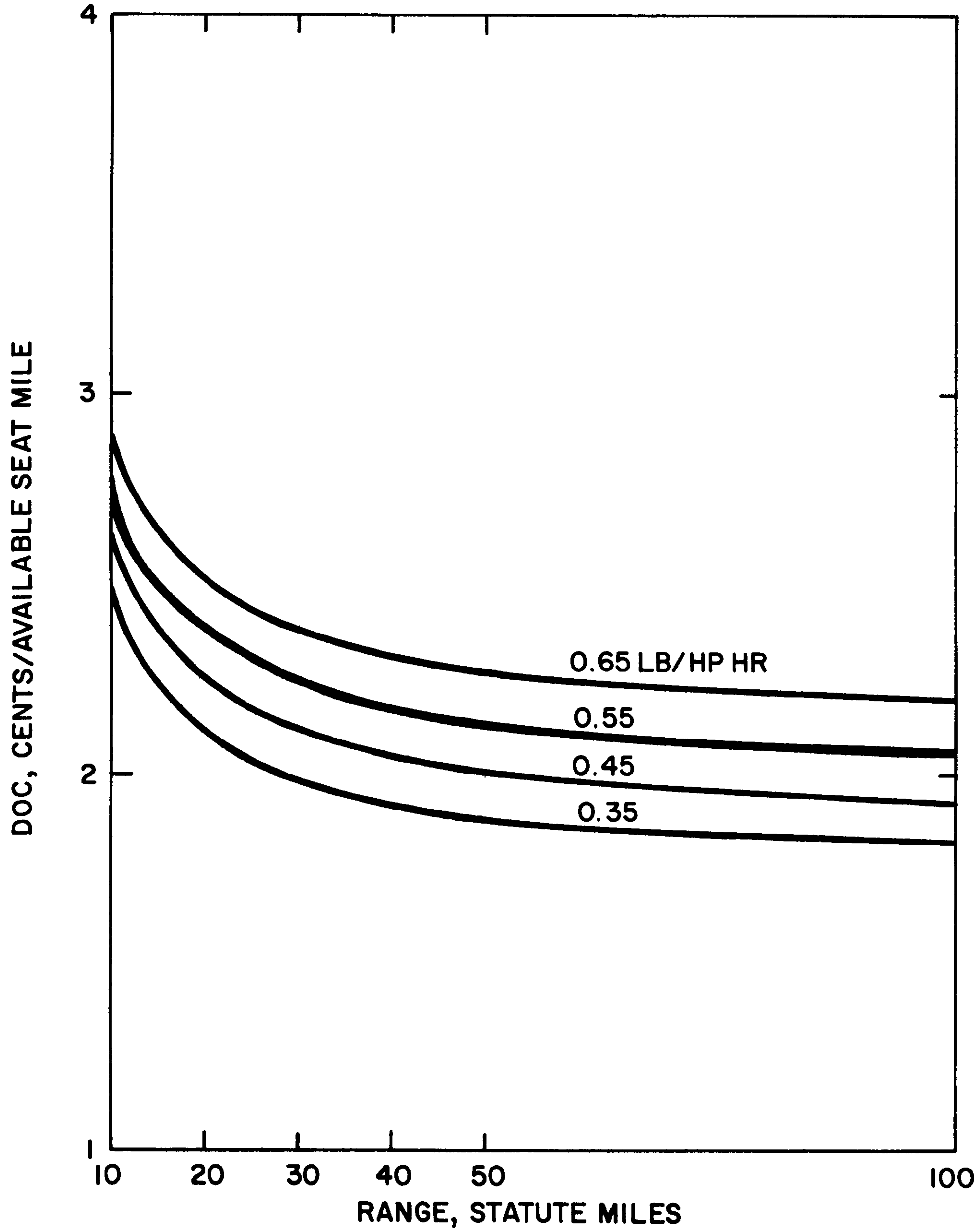


Figure II-65. HELICOPTER
SPECIFIC FUEL CONSUMPTION $\left(\frac{\text{LB FUEL}}{\text{HP-HR}}\right)$ VARIATION
AT NORMAL RATED POWER

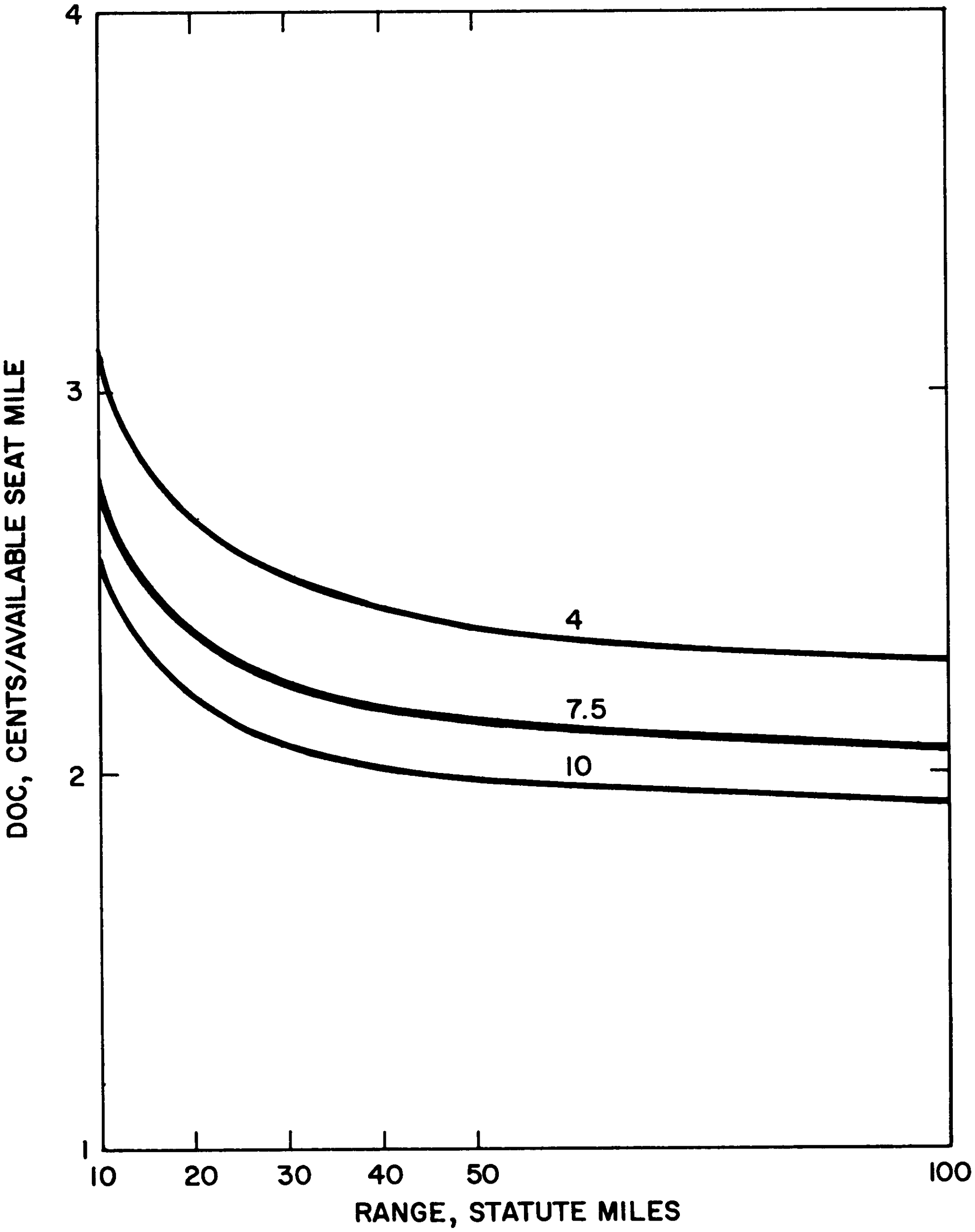


Figure II-66. HELICOPTER ENGINE HP/LB VARIATION

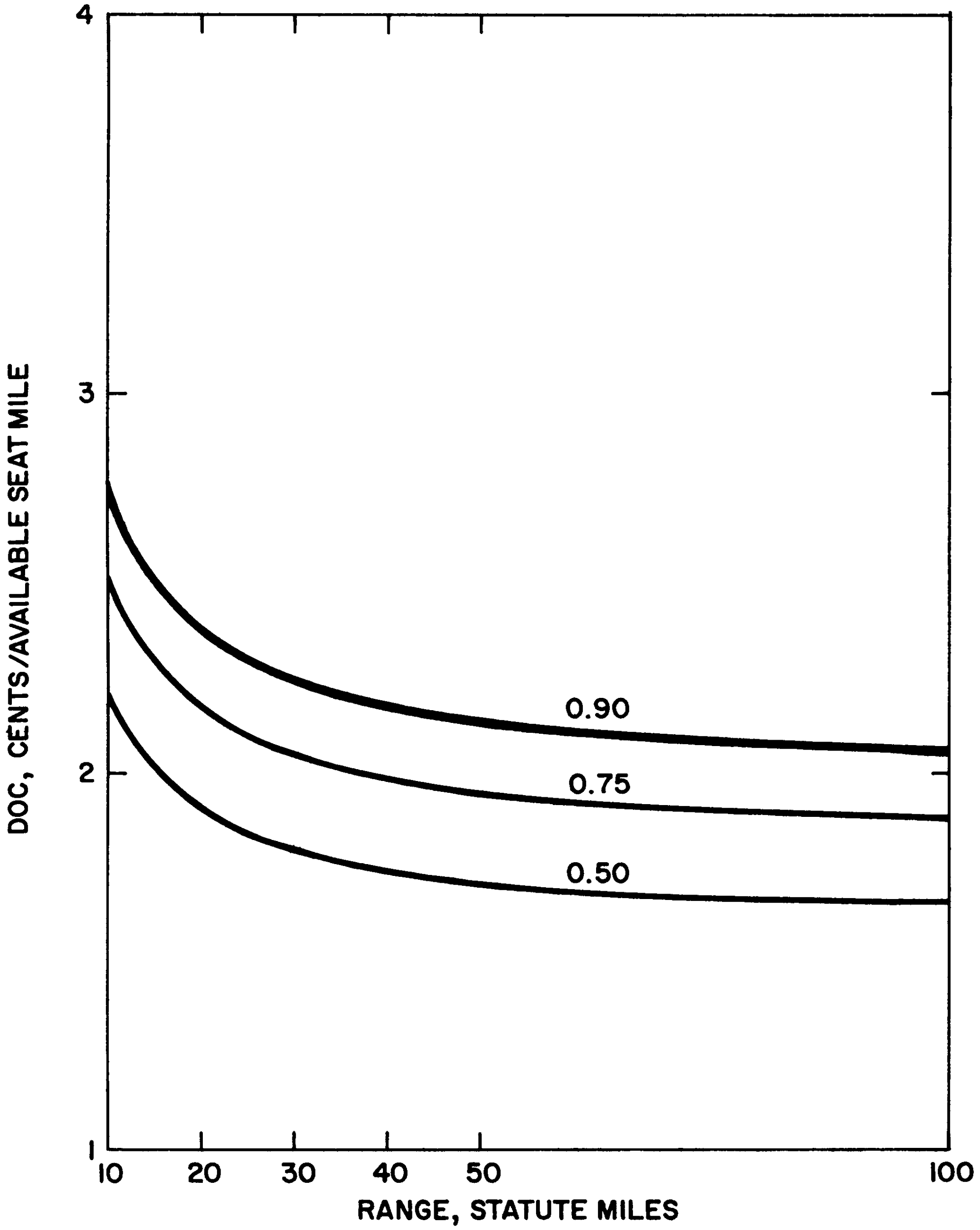


Figure II-67. HELICOPTER
ROTOR AND DRIVE SYSTEM WEIGHT FACTOR VARIATION

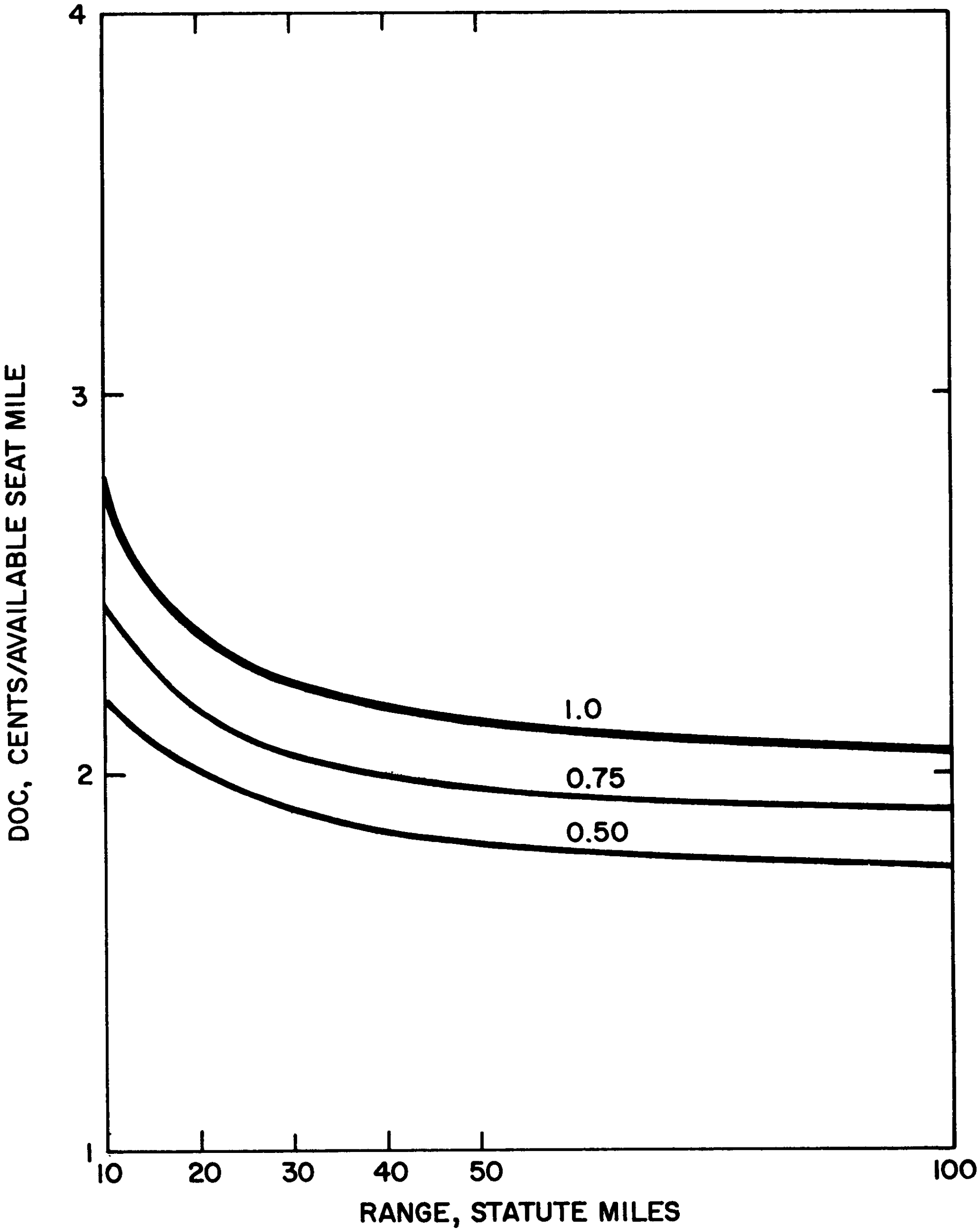


Figure II-68. HELICOPTER
STRUCTURAL WEIGHT FACTOR VARIATION

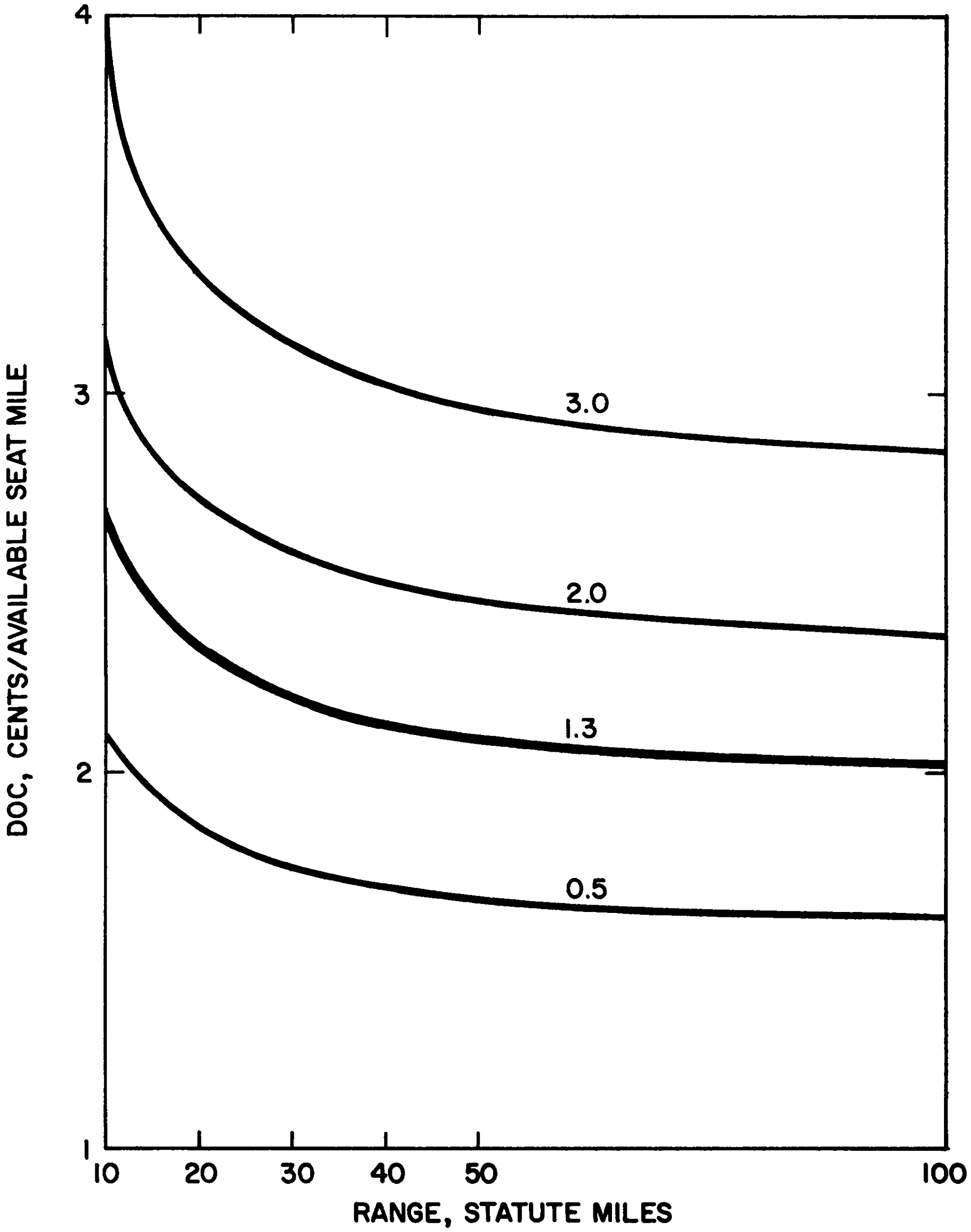


Figure II-69. HELICOPTER
MAINTENANCE FACTOR VARIATION

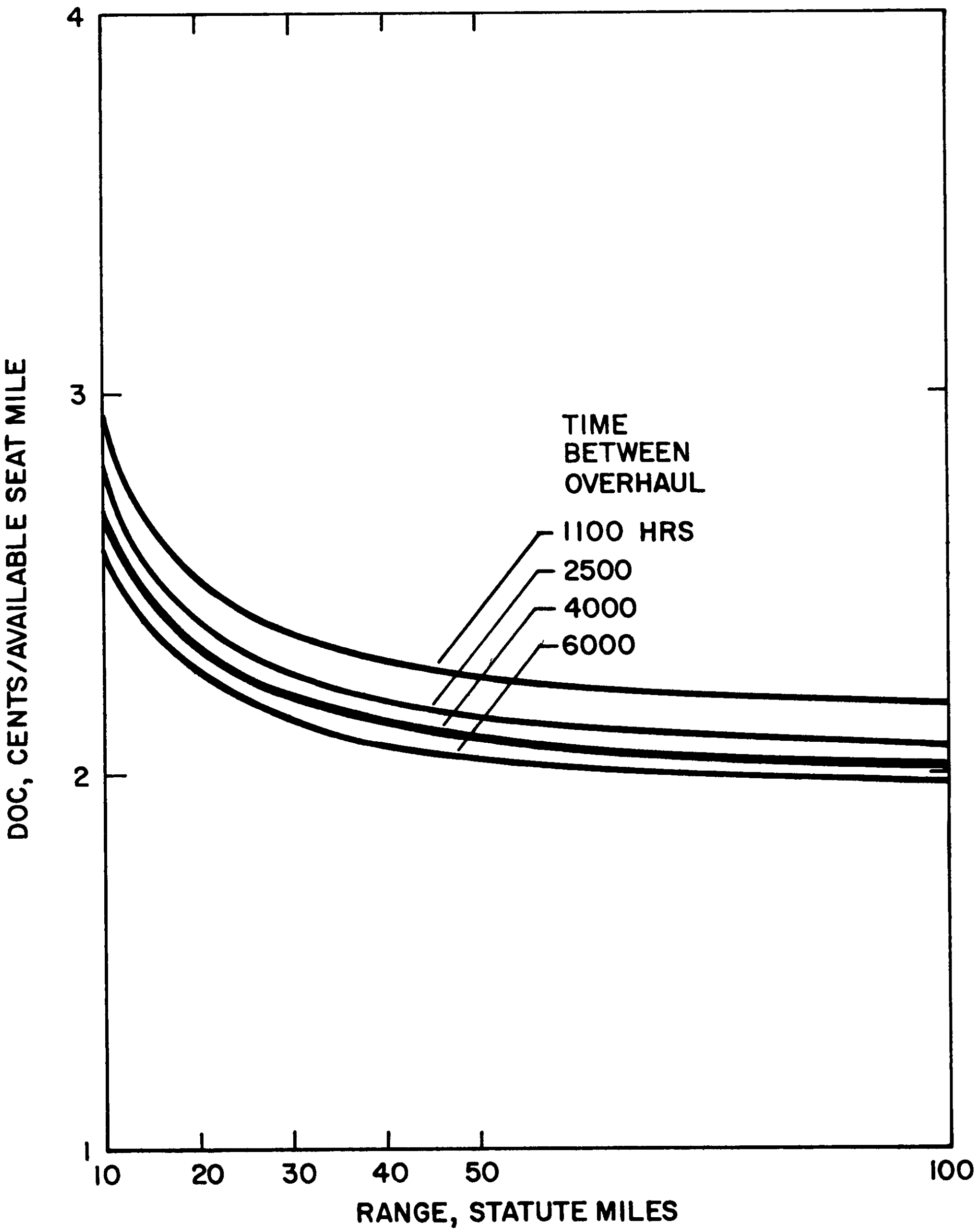


Figure II-70. HELICOPTER
TIME BETWEEN OVERHAUL OF ENGINE (TBO-HRS) VARIATION

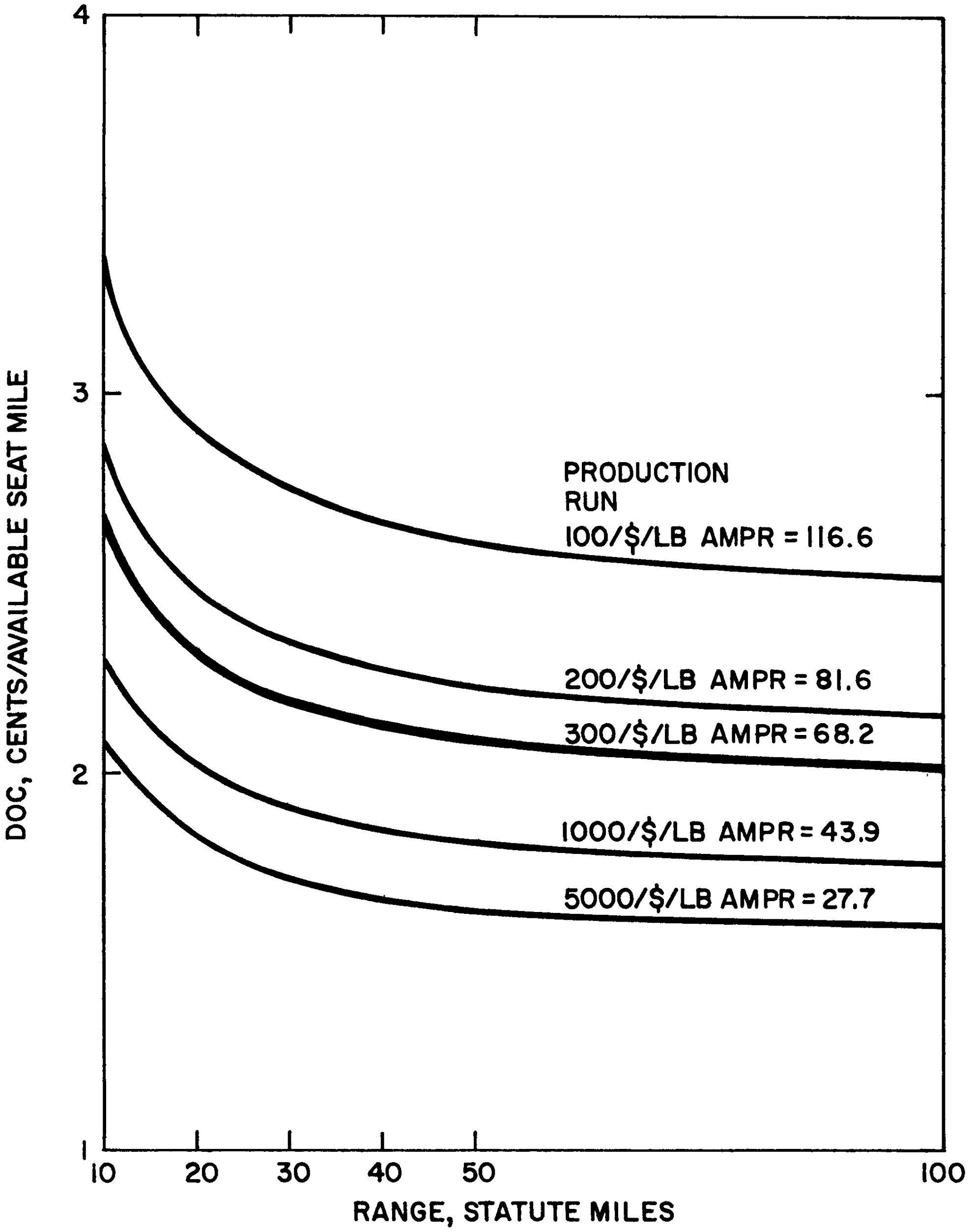


Figure II-71. HELICOPTER
PRODUCTION RUN (PROD. RUN) AND DOLLARS/LB AIRFRAME (D/LB AMPR
VARIATION

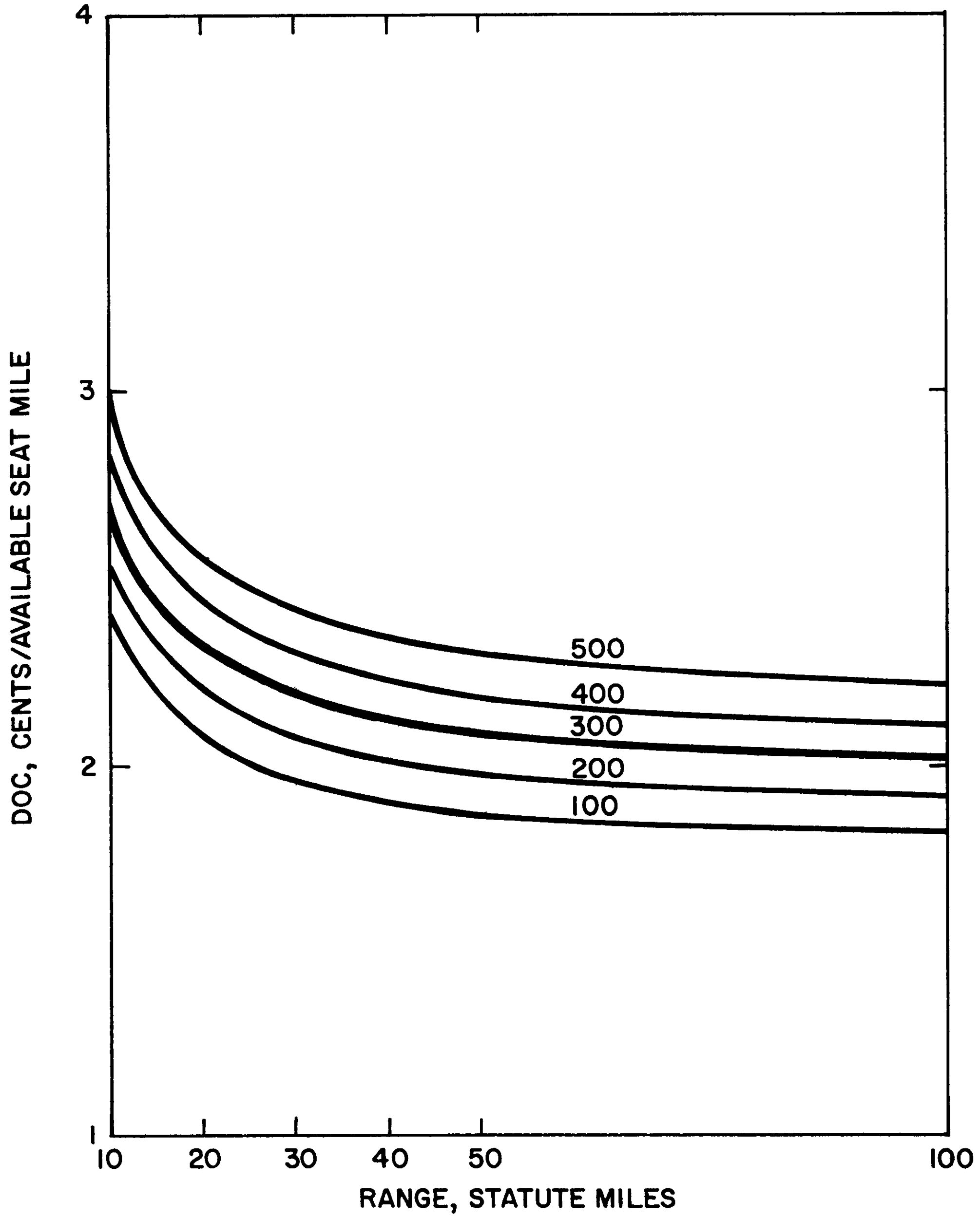


Figure II-72. HELICOPTER
DOLLARS/LB ENGINE VARIATION

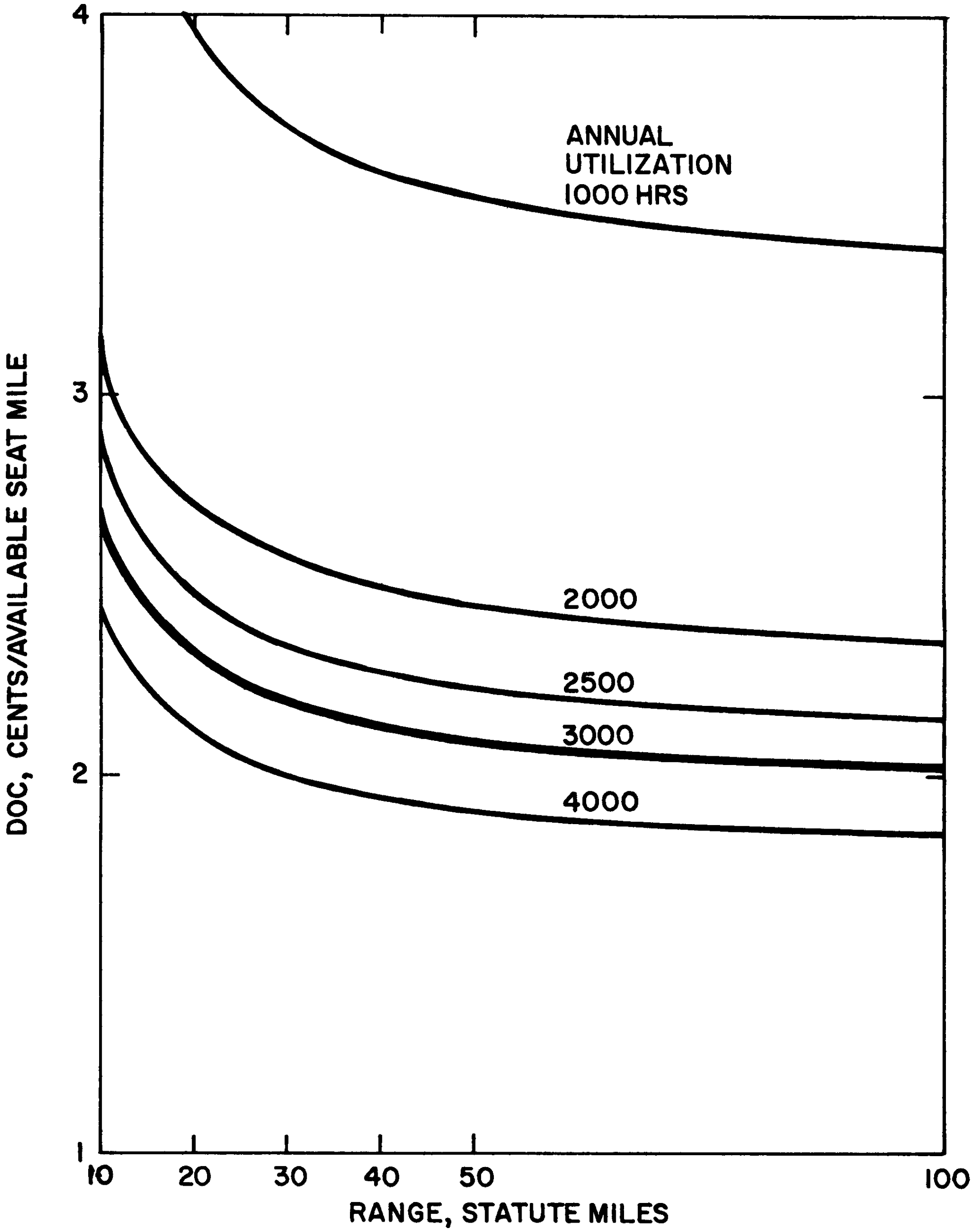


Figure II-73. HELICOPTER UTILIZATION (HRS/YR) VARIATION

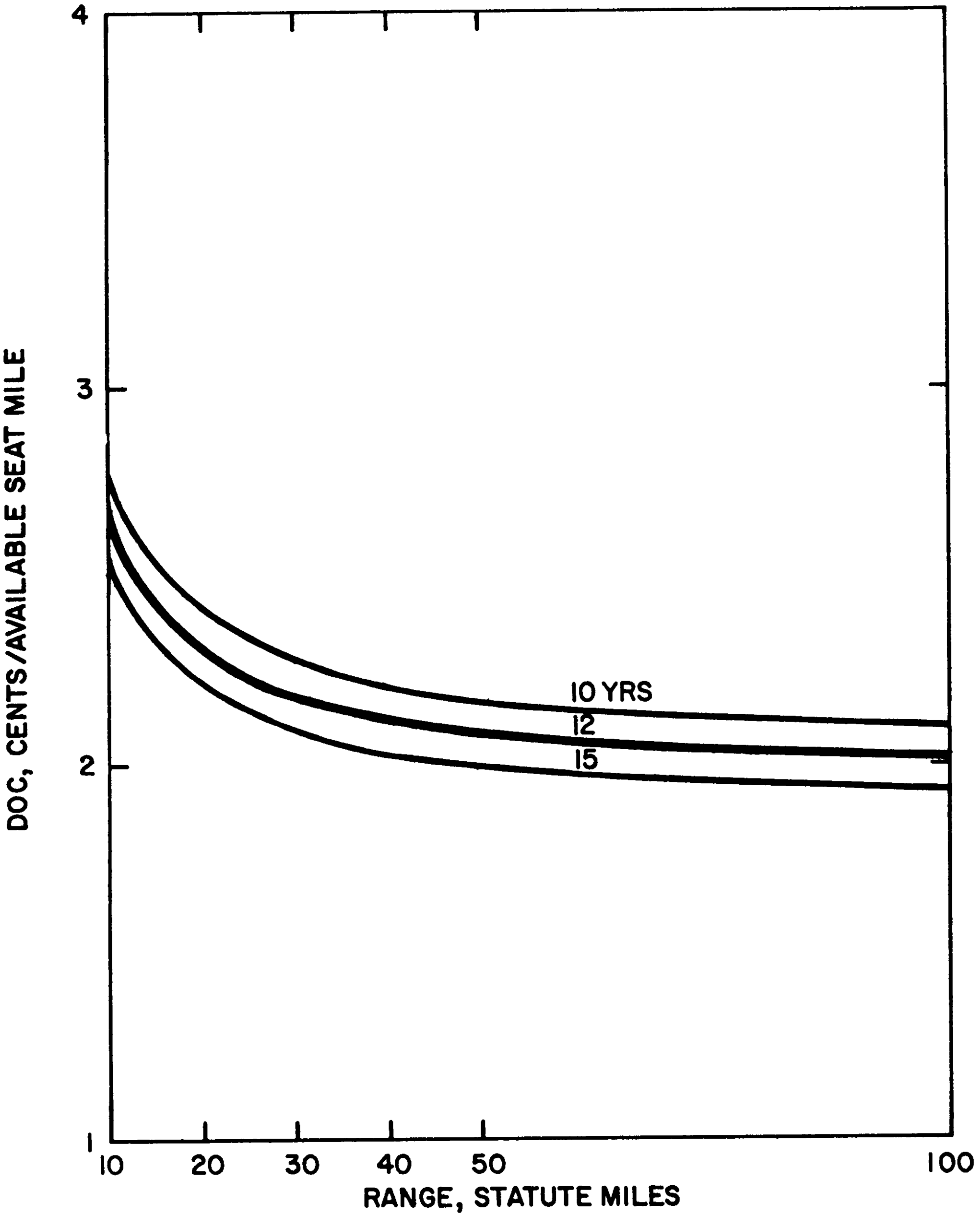
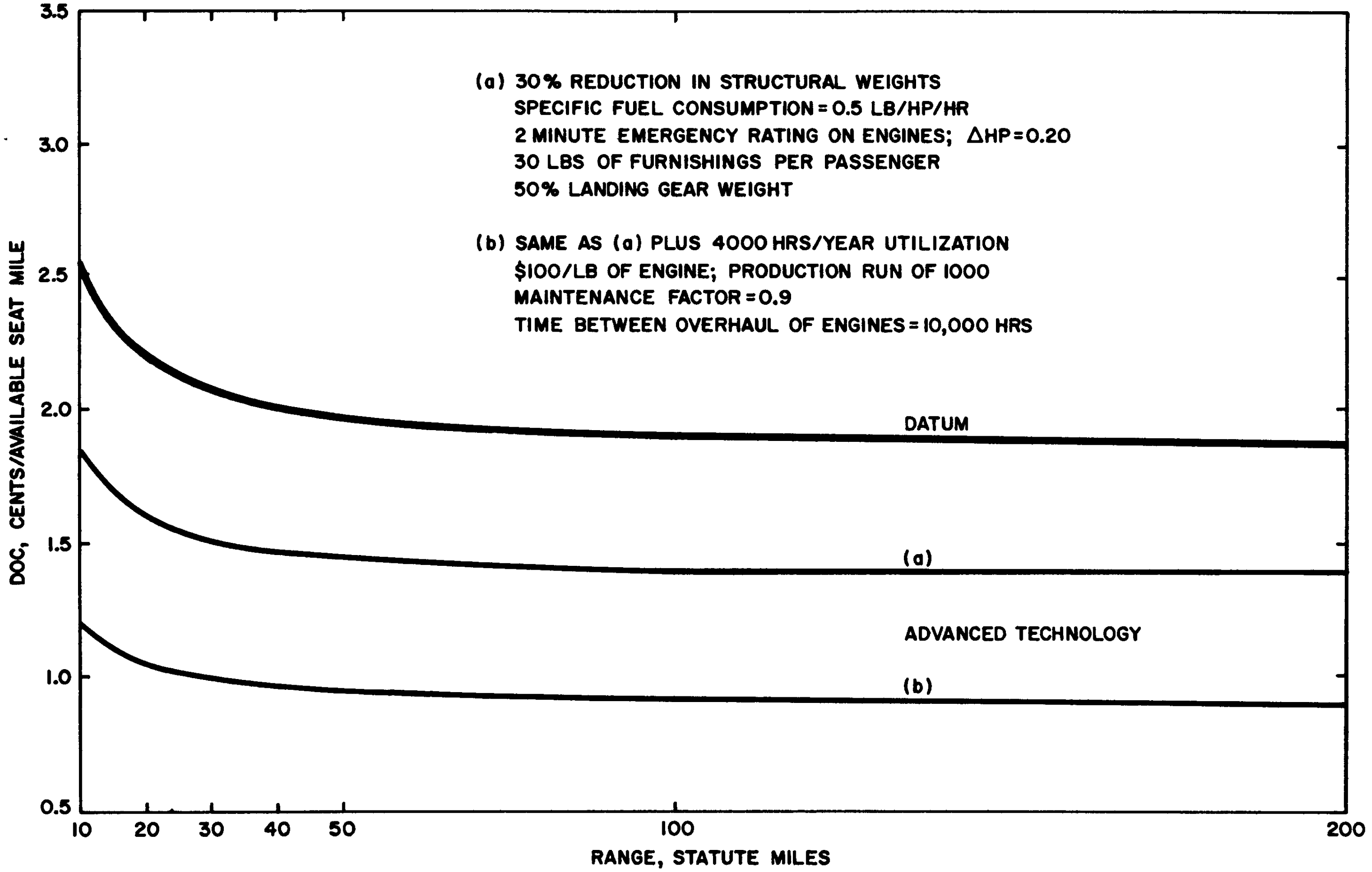


Figure II-74. HELICOPTER
DEPRECIATION PERIOD (YRS) VARIATION



(a) 30% REDUCTION IN STRUCTURAL WEIGHTS
SPECIFIC FUEL CONSUMPTION = 0.5 LB/HP/HR
2 MINUTE EMERGENCY RATING ON ENGINES; ΔHP = 0.20
30 LBS OF FURNISHINGS PER PASSENGER
50% LANDING GEAR WEIGHT

(b) SAME AS (a) PLUS 4000 HRS/YEAR UTILIZATION
$100/LB OF ENGINE; PRODUCTION RUN OF 1000
MAINTENANCE FACTOR = 0.9
TIME BETWEEN OVERHAUL OF ENGINES = 10,000 HRS

Figure II-75. ADVANCED TECHNOLOGY HELICOPTER

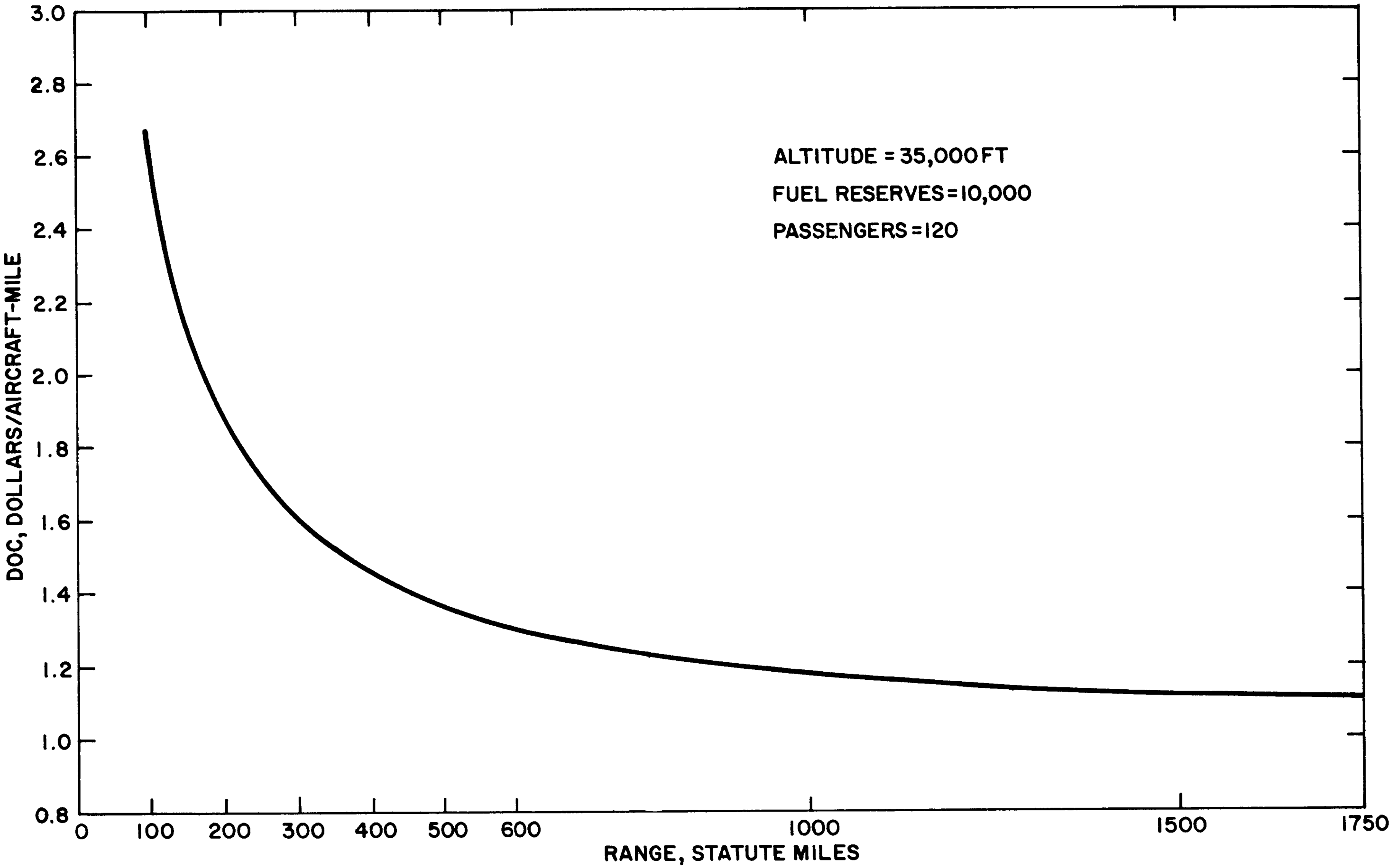


Figure II-76. PRESENT DAY SHORT-MEDIUM HAUL AIRCRAFT

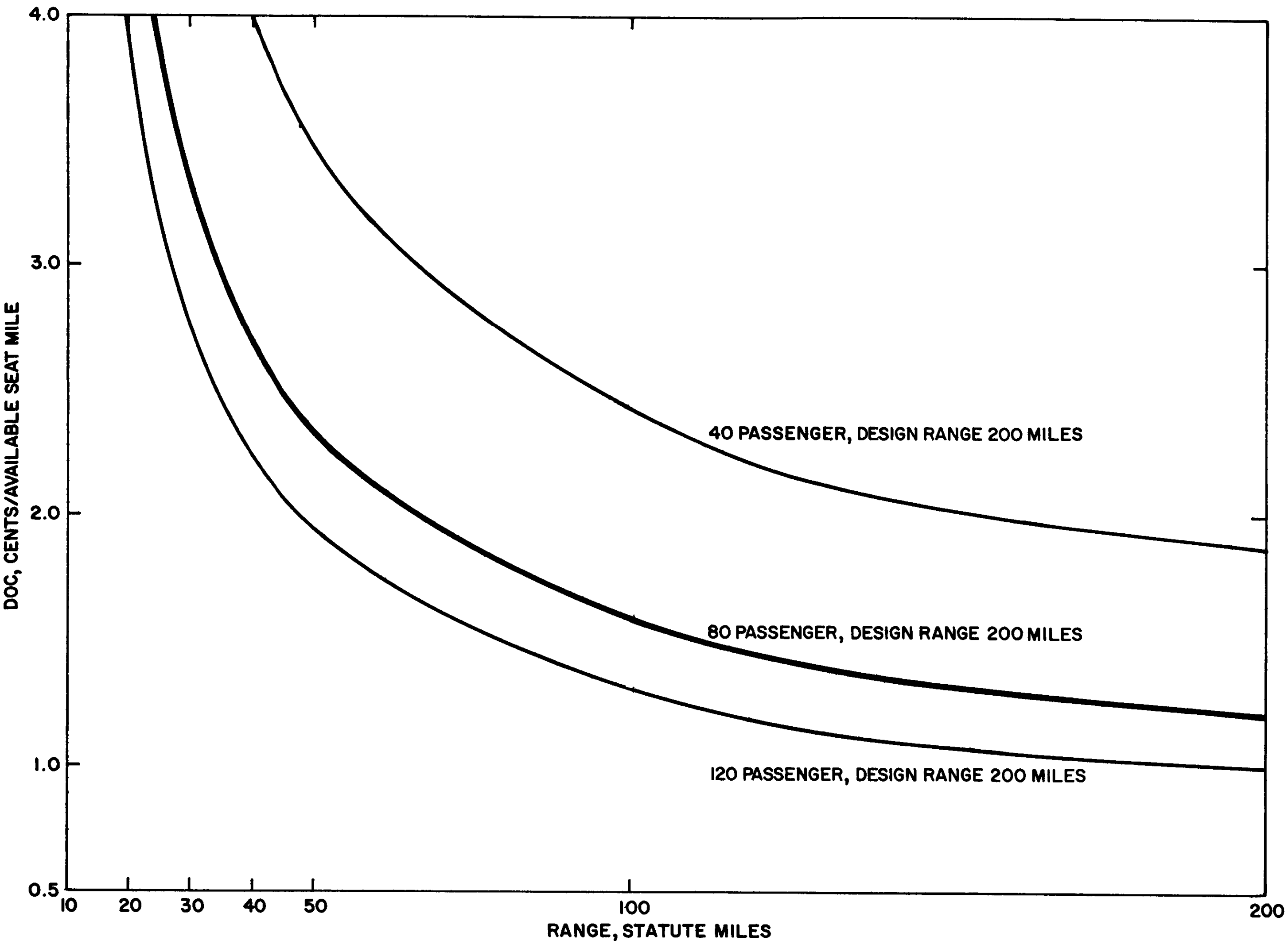
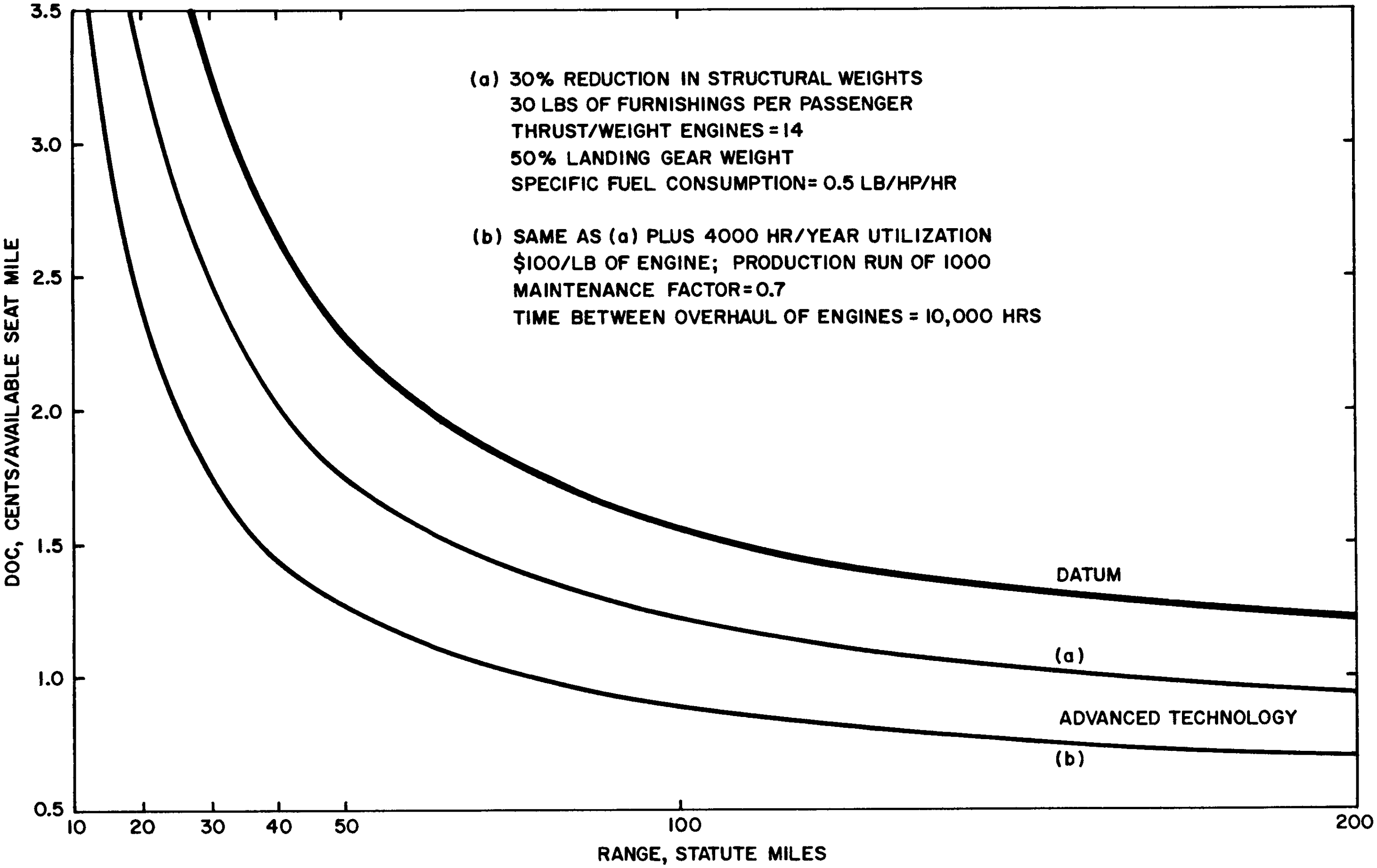


Figure II-77. CONVENTIONAL SHORT HAUL AIRCRAFT



(a) 30% REDUCTION IN STRUCTURAL WEIGHTS
30 LBS OF FURNISHINGS PER PASSENGER
THRUST/WEIGHT ENGINES = 14
50% LANDING GEAR WEIGHT
SPECIFIC FUEL CONSUMPTION= 0.5 LB/HP/HR

(b) SAME AS (a) PLUS 4000 HR/YEAR UTILIZATION
$100/LB OF ENGINE; PRODUCTION RUN OF 1000
MAINTENANCE FACTOR=0.7
TIME BETWEEN OVERHAUL OF ENGINES = 10,000 HRS

Figure II-78. ADVANCED TECHNOLOGY SHORT HAUL TRANSPORT

PART III.

DIRECT OPERATING COST ANALYSIS

III TABLE OF CONTENTS

INTRODUCTION

In estimating the costs of operation of an air system, costs are generally divided into two main parts: Direct Operating Costs, which are directly associated with the air vehicle and its operation and which are affected by the efficiency of design and production; and Indirect Operating Costs which are associated with the ground operations and management of the rest of the airline system excluding the vehicle. This procedure has been followed in this report, and Direct Operating Costs are estimated by modifying a standard 1960 ATA (Air Transport Association) formula which is widely used by manufacturers and airlines. The modification is necessary since the formula is derived from U.S. domestic airline operations and costs, and is not applicable to the very short haul V/STOL air systems considered in this report.

Part III studies the validity of the 1960 ATA formula to present jet transport operations, and to present helicopter airline operations. It explains the assumptions and modifications made to the ATA formula in estimating V/STOL DOC values, and attempts to outline areas where there exists a possibility for future cost reductions. In particular, the maintenance costs for VTOL vehicles is closely studied since it is found to be relatively very much higher at present than the jet transport maintenance costs.

VALIDITY OF THE ATA COST FORMULA

Choice of Formula

In this section, the direct operating costs of the potential vehicles have been forecast through the use of a slightly modified 1960 ATA (Air Transport Association) formula. Because the ultimate conclusions of any such study hinge so critically upon the reliability of the cost estimates it is of prime importance to subject the formula to careful analysis and to test its validity.

The elements which are included in the Direct Operating Cost estimated by the ATA formula include costs of crew, fuel and oil, insurance, maintenance and depreciation.

The 1960 ATA formula was chosen in the first place for the following reasons:

a) As a basis it is the most widely used formula. Individual airlines use it to analyse new equipment for their respective route networks, substituting their own company factors where appropriate. Airplane manufacturers use it in their economic studies and presentations. The Federal Aviation Agency specified its use in its Request for Proposal for the Supersonic Transport.

b) It incorporates all the parameters which characterize the operation of the diverse design vehicles and influence their operating costs (e.g. block speed, and utilization). It thus provides some standard whereby to compare the economics of these vehicles.

Shortcomings of the Formula

Scepticism as to its validity arises from the following shortcomings:

a) The formula was derived by making the best fit to a set of statistics gathered over some period prior to 1960, and is not the result of pure analytic approach to airplane costing.

b) The predominant aircraft in service during the gathering of the statistics were piston-engined. The predominant aircraft in service since the formula was published have been turbine powered.

c) The formula does not account for the large spread in actual costs experienced by different airlines operating the same aircraft type. Clearly, there are factors, both tangible and intangible, which have an important influence on the final direct cost, and which are related to the operator rather than to the vehicle. (See Figure III-1.)

d) The vehicles being studied in this report, in addition to being turbine powered, are not even conventional fixed wing types.

Experience with the Formula

With what justification then are these shortcomings neglected for the sake of adopting the formula?

First, the formula needs to be tested to see if in fact it does predict the average direct operating costs of current equipment. Table III-1, which presents direct operating costs (actuals vs. ATA estimates), covers a wide range of vehicles and demonstrates a fairly good measure of agreement for fixed wing conventional aircraft whether prop jet or pure jet. This is particularly convincing since the averages reflect a sizeable number of operators, with aircraft in service about three to four years. Therefore, the costs are not inflated by introductory costs nor by heavy modification expenses incurred sometimes when introducing a new type into service. Conversely, the costs are not too low by virtue of the equipment being too new to service, and, therefore, before any serious overhaul costs could have been incurred.

TOTAL DIRECT OPERATING COST - 1964 ACTUAL vs. ATA FOR BOEING 707

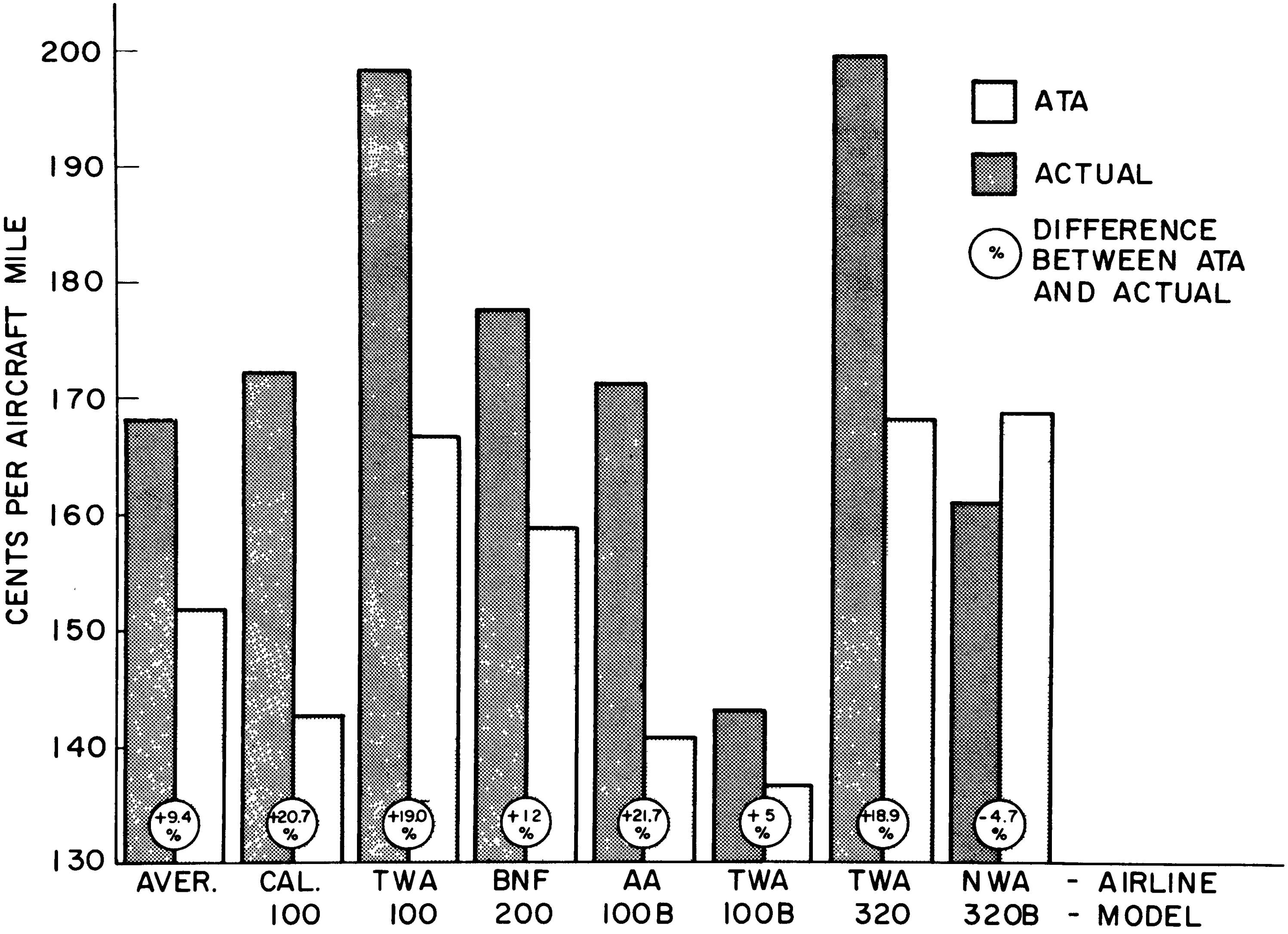


FIG. III - 1

TOTAL DIRECT OPERATING COSTS

	Domestic B-707 Average		Domestic DC-8 Average		B-720 Average		B-727 Average		Caravelle (only 1 operator)		Electra Average		F-27 Average		Helicopter	
	Actual	ATA	Actual	ATA	Actual	ATA	Actual	ATA	Actual	ATA	Actual	ATA	Actual	ATA	Actual	ATA
Crew	31.9	15.9	28.1	15.9	28.4	15.6	30.3	16.4	38.0	18.3	35.14	17.4	25.07	22.2		32.7
Fuel & Oil	45.2	44.0	48.9	47.6	46.0	43.7	34.0	35.2	38.1	35.2	24.37	26.7	16.87	16.2		18.9
Insurance & Injuries	6.7	14.8	5.6	15.3	6.2	15.8	7.6	19.2	4.1	16.9	2.65	8.4	3.73	8.5		23.0
Other Expenses																
Total Flying Operations	83.8	74.7	82.6	78.8	80.6	75.1	71.9	70.9	80.2	70.4	62.16	52.5	45.7	46.8	73.67	74.6
Maintenance - Airframe		17.9		18.0		15.6		14.9		14.6	12.27	10.2	15.13	12.4	59.1	20.3
Maintenance - Engine		12.2		12.4		17.8		19.8		9.3	24.59	12.4	9.18	2.7	55.0	14.2
Maintenance - Others											6.99		4.15			
Total Direct Maintenance	30.2	30.1	32.9	30.4	33.9	33.4	20.6	34.7	39.6	23.9	43.85	22.6	28.46	15.2	114.1	34.5
Depreciation - Airframe	23.2	23.3	19.7	21.9	18.5	19.7	25.6	26.5	34.3	30.2		10.9		15.7		38.0
Depreciation - Engine		4.7		4.6		7.7		6.7		4.3		6.2		1.4		7.1
Depreciation - Other Flight Equipment		7.0		6.7		9.0		9.6		9.1		6.9		4.4		14.2
Total Depreciation	33.2	35.0	32.3	33.3	23.8	36.4	35.8	42.9	45.9	43.7	36.68	24.1	12.52	21.5	38.38	59.3
Applied Burden	21.2	12.6	20.6	12.9	18.9	12.9	13.4	13.7	31.1	10.96	15.32	9.9	10.45	8.5	29.46	17.9
TOTAL D.O.C. (minus Burden)	147.2	139.8	147.8	142.5	138.3	144.9	128.3	148.5	165.7	138.0	142.69	99.2	86.68	83.5	226.15	168.4
TOTAL D.O.C. (plus Burden)	168.4	152.4	168.4	155.4	157.2	157.8	141.7	162.2	196.8	148.96	158.01	109.1	97.13	92.0	255.61	186.3
Cents/seat mile	1.35	1.22	1.35	1.24	1.4	1.4	1.5	1.7	2.09	1.58	1.6	1.1	2.0	1.9	9.13	6.65
Number of seats	125	125	125	125	115	115	93	93	94	94	98	98	48	48	28	28
Trip Length- St. Miles	900	900	850	850	705	705	600	600	395	395	500	500	120	120	22	22
Utilization- hrs./yr.	4,000	4,000	3,800	3,800	3,600	3,600	2,500	2,500	2,300	2,300	3,000	3,000	2,700	2,700	1,632	1,632
Engine Overhaul Period- Hrs.	5,000	5,000	5,000	5,000	5,600	5,600	1,600	1,600	2,000	2,000	3,800	3,800	4,000	4,000	1,100	1,100
Depreciation Period- Yrs.	11	11	12	12	12	12	12	12	10	10	10	10	10	10	10	10
Block Speed- m.p.h.	410	410	410	410	420	420	380	380	307	307	320	320	200	200	102	102

30 x 500

C/A/C MILE

NOTE: All figures above double line (═══) are Cents per Aircraft Mile.

TABLE III-1

TOTAL DIRECT OPERATING COSTS

TABLE III-1

This leads to an important conclusion. With the current subsonic jet equipment, we are close to the optimum in design and operating efficiency commensurate with today's technology level. Any significant change in direct operating costs is unlikely (unless through a major technological breakthrough), and it is precisely this cost which is so well forecast by the ATA formula. It seems reasonable to assume, therefore, that if the formula is at all applicable to a VTOL machine, it will forecast costs of an equally efficient vehicle.

Application of the Formula to V/STOL Aircraft

Since this study includes V/STOL aircraft, as well as fixed wing machines, it is most important to test if the ATA formula compares with actuals for V/STOL vehicles. Unfortunately, there is only one VTOL type in commercial (or even military) service, and this is the helicopter. Furthermore, its scope of operation is much smaller than that of the fixed wing fleets so that the statistical sample is less reliable. This comparison shows significant differences between the ATA predictions and the actual costs and, naturally, leads to the following questions:

Do these differences stem from factors

a) inherent in a helicopter;
b) inherent in any VTOL;
c) associated with the mode of operation of the vehicle;

d) associated with a vehicle in its relative infancy;

e) associated with the small quantity of vehicles in commercial service;

f) associated with a design that relegates maintainability to a less important role; or

g) inherent in the formula itself?

To answer these questions it is necessary to analyse the ATA formula.

There are three basic cost groups in the ATA formula:

a) Flying operations, comprising
    - Operating Crew Pay
    - Fuel and Oil
    - Insurance and Injuries (Public Liability and Property Damage)

b) Direct Maintenance-Flight Equipment, comprising
    - Labor - Aircraft
    - Materials - Aircraft
    - Labor - Engine
    - Materials - Engine

c) Depreciation-Flight Equipment, comprising
    - Depreciation - Aircraft
    - Depreciation - Engines
    - Depreciation - other flight equipment

In addition it is customary to include the Applied Maintenance Burden, related in some fixed manner to labor and materials.

There is no reason why fuel and oil, insurance and injuries or depreciation should be influenced by whether the vehicle is VTOL or CTOL (conventional take off and landing), and, in fact, for these items the differences between ATA and actual are not great. (See Table III-1). Operating crew pay could be influenced by the type of vehicle, as well as the mode of operation (e.g. large number of departures per flying hour), but in fact the difference between ATA and actual is not great.

The one significant area where the difference is marked is maintenance, and this requires further detailed study and analysis.

Comparison of Actual and ATA Formula Maintenance Costs for A Present Helicopter

Table III-2 presents a breakdown of maintenance cost figures for a conventional 115 passenger jet, and a 28 passenger commercial helicopter. The ATA formula predicts the total very closely for the jet, while for the helicopter, the actual cost is about three times that of the ATA value. (See Table III-1) Closer study using the aircraft maintenance system breakdown brings to light factors which explain in part this discrepancy, and thereby facilitates sounder judgement in estimating future VTOL maintenance costs.

MAINTENANCE COSTS

	Average 720 B		Current Helicopter	
ATA 100 system	$/flt.hr.	¢/aircraft mile	$/flt.hr.	¢/aircraft mile
21 Air Conditioning	2.66	.633	0.30	0.29
22 Automatic Pilot	0.79	.188	--	--
23 Communication	0.94	.244	1.12	1.098
24 Electrical Power	4.63	1.102	1.05	1.03
25 Equipment & Furnishings	4.19	.997	1.08	1.06
26 Fire Protection	0.26	0.62	--	--
27 Flight Controls	1.77	.421	5.01	4.91
28 Fuel System	0.83	.198	0.64	0.63
29 Hydraulic Power	2.83	.674	0.27	0.26
30 Ice and Rain	0.3	.071	--	--
31 Instruments	0.31	.071	2.04	2.0
32 Landing Gear	12.45	2.964	4.23	4.15
33 Lights	0.86	.205	0.03	0.029
34 Navigation	2.63	.626	1.21	1.19
35 Oxygen	0.39	.093	--	--
36 Pneumatic	0.11	.026	--	--
38 Water and Waste	0.52	.124	--	--
52-57 Airframe Structure	4.69	1.117	5.38	5.27
60 Rotors	--	--	6.27	6.15
71-80 Power Plant & Engine	74.10	17.64	56.07	54.97
84 Transmission	--	--	10.58	10.37
Scheduled Inspections	24.30	5.786	20.00	19.61
Miscellaneous	--	--	1.15	1.13
TOTAL Direct Maintenance Cost	139.56	33.2	116.43	114.1

TABLE III-2

In this ensuing discussion the term "normalized" is used. By this it is meant that a cost for the helicopter system has been derived from the equivalent 720B system cost. Since the ATA formula labor costs are proportional to empty airframe weight, while material costs are proportional to empty airframe cost, the material and labor elements are separated out from the system cost and studied in the following manner:

a) Normalized Helicopter System Labor Cost =

$$\frac{\text{Empty airframe weight of helicopter}}{\text{Empty airframe weight of Boeing 720B}} \times \text{720B System Labor Cost}$$

$$= \frac{10,743}{98,600} \times \text{720B S.L.C.} = 0.109 \times \text{720B S.L.C.}$$

b) Normalized Helicopter System Materials Cost =

$$\frac{\text{Empty airframe cost of helicopter}}{\text{Empty airframe cost of 720B}} \times \text{720B System Materials Cost}$$

$$= \frac{741,500}{4,225,000} \times \text{720B S.M.C.} = 0.176 \times \text{720B S.M.C.}$$

Normalized Total Helicopter Cost = (a) + (b).

Each item will now be examined in detail, and an estimate made of costs which are realistically achievable if the helicopter systems were at a level of design comparable to present jet transports. The system costs referred to in the ensuing discussion are given in Table III-3.

ATA 21 - Air Conditioning. The two systems are really not comparable. The jet is pressurized, has heating and cooling, pressure and temperature controls, long lengths of ducting both inside and outside the fuselage, and is quite complex. The helicopter is not pressurized, has only a heating device, relatively short lengths of ducting in the fuselage, and is not complex. Its cost, which should be much less than the jet, is therefore considered to be realistic and acceptable.

ATA 23 - Communications. Except for a High Frequency installation in the jet, the systems are comparable, and quite unrelated to size or weight of the individual vehicles. The costs, therefore should show the same order of magnitude. As an acceptable value, a figure a little less than the jet is taken since the high frequency equipment is missing.

ATA 24 - Electrical Power. The power system in the jet is a four-engine system with generators and constant speed drives (CSD) whilst the helicopter has a two-engine system, and no CSD, and this is well reflected by the costs. The actual is taken as the acceptable figure.

MAINTENANCE COST BREAKDOWN FOR A CURRENT HELICOPTER

ATA System No.	Present Cost $/flt. hr.		Cost Based on 720 B normalized on empty airframe weight and cost	Cost used to represent realistic achievable
	Jet 720 B	Helicopter	$/flt. hr.	$/flt. hr.
21 Air Conditioning	2.66	0.3	0.41	0.3
23 Communication	0.94	1.12	0.13	0.8
24 Electrical Power	4.63	1.05	0.76	1.05
25 Equipment & Furnishings	4.19	1.08	0.74	0.74
27 Flight Controls	1.77	5.01	0.26	1.00
28 Fuel System	0.83	0.64	0.12	0.12
29 Hydraulic Power	2.83	0.27	0.44	0.27
31 Instruments	0.31	2.04	0.04	0.30
32 Landing Gear	12.45	4.23	2.07	2.07
33 Lights	0.86	0.03	0.13	0.03
34 Navigation	2.63	1.21	0.37	0.74
52-56 Airframe Structure	4.69	5.38	0.67	1.34
71-80 Power Plant & Engine	74.1	56.07	26.00*	26.00
Scheduled Inspections	24.3	20.00	2.65	5.29
TOTAL	137.2	98.4	34.74	40.05

*Engine Cost not normalized

TABLE III-3

ATA 25 - Equipment and Furnishings. The jet has seating for 115, a cabin interior of the size to house them, galleys, toilets and passenger service units housing oxygen, loudspeakers, steward call, lighting and fresh air. The helicopter has one quarter of the seating (28) and a comparable cabin size, no galleys, no toilets, and a much simpler fixed lighting and fresh air installation. One would consequently expect the helicopter costs to be very much less than one quarter of the jet costs.. It is true that the helicopter, due to its short haul mode of operation, suffers some cost penalty on wear and tear of seats through relatively greater passenger movements, as well as through cargo carrying, when the seats are folded against the walls. Also the seats are lighter than they are on the jet, so that these factors all tend to boost the helicopter cost. However, since the realistic achievable costs being estimated are those of a vehicle carrying passengers only, with seats comparable in maintainability to those on the jet, a more reasonable cost figure would be that obtained by normalizing the 720 B value.

ATA 27 - Flight Controls. The jet system comprises cable runs, moving control surfaces, and hydraulic boosters for ailerons, spoilers, leading and trailing edge flaps, rudder, elevators, and tail plane. The helicopter system has cable runs and hydraulic boosters which control cyclic and collective pitch and tail rotor. The jet system is more complex and has a greater number of individual units, and would be expected therefore to cost more. How then do we account for the helicopter being almost three times as costly?

The helicopter cost figure does not only reflect normal, recurring, scheduled and unscheduled maintenance, but also includes costs of some major modifications and repairs which are no longer necessary. It is not uncommon to incur such expenses during the early phases of introducing a new aircraft model into commercial service, and these charges should more correctly be attributed to development costs. In some instances this is well recognized by the manufacturer who accepts part of the expense.

In the case of this particular system, in order to achieve the present fairly trouble free operation, it was necessary to expend quite heavy sums on repairs and modifications to auxiliary servos and valves. The normalized cost, heavily weighted by a conservatism factor, leads to the acceptable cost figure assumed here.

ATA 28 - Fuel System. The helicopter system should be relatively less costly than it actually is, since it has far less units and is a smaller system than the jet. The normalized cost would seem to be a more reasonable figure.

ATA 29 - Hydraulic Power. The comparative costs are representative and the actual cost has been used.

ATA 31 - Instruments. The high costs of the helicopter are accounted for by the manner in which the instruments are installed. Since it is difficult to read the instruments when they are mounted on conventional shock mounts, it has been necessary to attach them rigidly to the airframe where they are subjected to vibratory loads for which they were never designed. Helicopter vibration will be reduced in the future, and the normalized cost, weighted by a conservatism factor has been used for a realistic figure.

ATA 32 - Landing Gear. The jet has a fully retracting landing gear, with wheels, tires and brakes being used for long taxi runs, and takeoff and landing rolls. The helicopter has a much simpler non-retracting gear, with far less taxiing and no takeoff or landing roll. However, the latter vehicle has about 8 times as many takeoffs and landings per flight hour, and considerable usage of brakes and scuffing of tires in tight turns, and much of the cost stems from tires and brakes. The actual costs shown are consequently not unreasonable. However, today's technology is well capable of achieving a realistic cost less than the actual helicopter figure. The normalized jet value is, therefore, used here.

ATA 33 - Lights. The comparative costs are representative and the actual has been retained.

ATA 34 - Navigation. The comparative costs are representative and the actual has been retained.

ATA 52, 53, 54, 55, 56, 57 - Airplane Structure. The jet has a much larger fuselage as well as wings, pods and tail section. The fuselage is subjected to pressurization cycles and pressure loads over and above the normal flight loads. The helicopter has no wings or pods, a much smaller tail and no pressurization. It does have a higher vibration level. Major modifications involving strengthening the attachment of the main transmission mount to the upper fuselage, improving the landing gear fittings, preventing leakage from the fuel cells, and eliminating frequent maintenance to the Air Stair doors are responsible for about $3.30 per flight hour. Since current structural maintenance is not excessive, and since these modifications are non-recurring, the truer picture of actual helicopter airframe structural costs would be $2.00 per flight hour, making comparison with the jet reasonably acceptable. The normalized figure weighted by a factor of two is, therefore, taken as an assumption, taking into account reduced vibration.

<u>ATA 71, 72, 73, 74, 75, 76, 77, 78, 79, 90</u> - <u>Power Plant and Engine</u>. The jet engine costs are truly representative of the state of the art. Currently TBO's of 5,000 - 6,000 hours are being achieved (see Figure III-2) with hot section inspections at 2;000-- 3,000 hours. Costs around $18 per engine hour for an 18,000 pound thrust engine are attainable. The helicopter engines by comparison have been very much more costly at around $27 per flight hour. Part of this cost is due to:

a) A greater number of hot cycles per flight hour.

b) The actual engine hours being, in fact, at least equal to rotor hours, which is about 1.29 times flight hour time, although time is recorded as flight hours.

c) The smallness of the helicopter engine which limits its ability to tolerate the kind of blade distortion and wear which the larger engines can accept without requiring premature removal.

COMMERCIAL JET ENGINES

TIME BETWEEN OVERHAUL

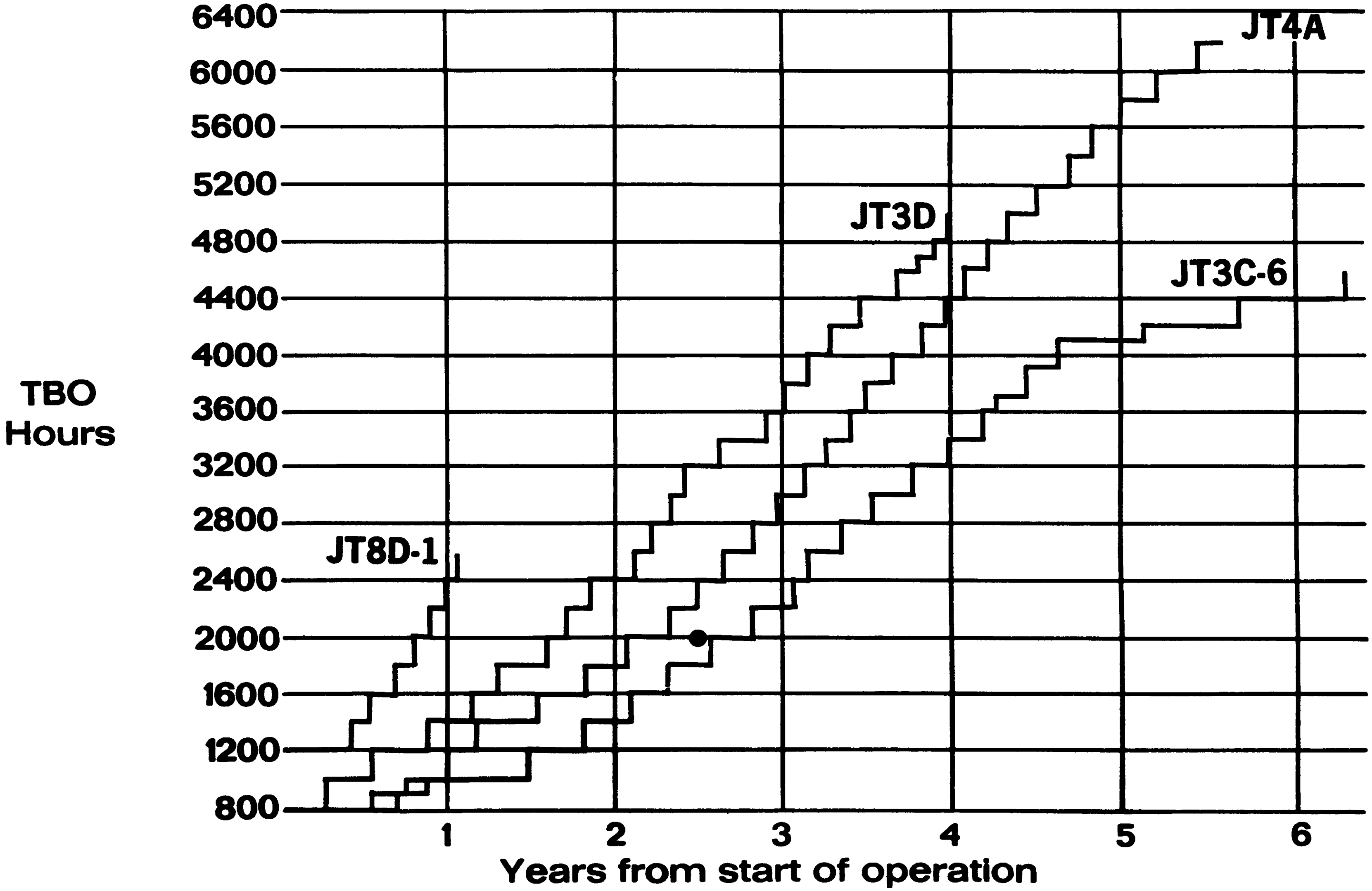


FIG. III-2

d) The fact that even if the engine were trouble free, the conventional sampling program essential to the formal extension of TBO by the FAA would still proceed at a slower pace than the bigger jet engines since the individual fleet size is small and the utilization low. The best that could have been expected with current utilization would be about 20 months to reach a TBO of 2,000 hours from the start of operation.

In reality, the current helicopter engine TBO stands at 1,200 hours after 36 months of operation, whereas jet engine TBO's reached 2,000 hours after approximately 18 months of service. (See Figure III-2)

The major portion of the cost however must be attributed to design and excessive overhead. There is good reason to believe that if the utilization were doubled and the fleet size increased, within a year the TBO could be at 2,000 hours, with a hot section inspection at 1,000 hours, and a total cost of $13 per engine hour. This is used as a realistic estimate.

<u>ATA 60 and 84</u> - <u>Rotor and Transmission</u>. These costs must be accounted for over and above whatever is forecast by the ATA

formula since these systems are non-existent in the case of the jet.

Scheduled Inspections. The predominant inspection for the helicopter is a C inspection, repeated every 150 hours, and performed in 5 phases. It is detailed and includes functional checks. A major part of the airframe structure, rotor and transmission also goes through a comprehensive visual B inspection every 17 hours.

Compared to this, an average 720 B has its dominant inspection phased over a 500 hour cycle.

In addition, the intensiveness of an inspection tends to adapt itself to the time period which is available: the longer the time, the longer the inspection. So the aircraft with lower utilization is likely to have a correspondingly higher inspection cost.

For these reasons the helicopter inspection cost is close to that of the jet. But as reliability improves and utilization increases, the natural tendency is for the time between checks to increase. Since inspection is strongly dependent on size, weight, and numbers of units, it is reasonable to take the normalized cost with a conservatism factor of 2 as a realistic estimate.

Estimate of Realistic Achievable Helicopter Maintenance Costs

With a helicopter design equivalent in state-of-the-art to the current fixed wing jets, the costs might be estimated on the basis of the discussion above to be similar to those shown in Column 4, Table III-3, as being realistically achievable.

For the helicopter under consideration, $40 per flight hour is equivalent to 39.2¢ per aircraft mile. The ATA formula estimate of direct maintenance cost for the helicopter is 34.5¢ per aircraft mile. (See Table III-1.) Pursuing the argument that this figure should not be expected to cover the costs of systems extraneous to the pure jet aircraft, this 34.5¢ is then directly comparable with the 39.2¢ just estimated, and well in accordance with the order of accuracy of this study.

The conclusion to be drawn from this analysis is that the ATA formula <u>is</u> capable of forecasting helicopter maintenance costs, as long as separate account is taken of the rotor and transmission systems, costs which are computed on page III-30.

ASSUMPTIONS USED IN APPLYING THE ATA FORMULA TO V/STOL VEHICLES

Block Time for VTOL and STOL Missions

The block times are estimated in the 1960 ATA formula as:

$$T_B = T_C + T_D + T_{am} + T_{gm} + T_{cr}$$

where:

T_B = block time

T_C = time in climb

T_D = time in descent

T_{am} = time in air maneuvering associated with landing and taking off

T_{gm} = time in ground maneuvering associated with taxiing from the loading gate to the runway and back

T_{cr} = time spent at cruise speed

The typical block time variation with trip distance resembles that shown in Figure III-8, i.e. a straight line whose slope is cruise speed, and whose zero distance intercept (called the block penalty) is a function of the time lost in climb, air maneuvering and taxiing. For trips into busy airports, there is another zero range time penalty associated with airport or terminal area delays which is a function of airport traffic loading and not aircraft design. The ATA formula uses actual times and distances for climb, cruise, and descent, and attempts to estimate air and ground maneuvering time as a function of gross weight. No estimate of airport delay time is made, although using actual block time statistics for commercial flight segments to estimate the gross weight variation will introduce a representative delay for U.S. domestic trunk airlines.

Since the ATA formula costs can be expressed as

$$\text{Trip Cost} = \text{Fuel cost} + \text{CHR} \times \text{Block Time}$$

where CHR is a constant cost/block hour, there is a large proportion of airplane trip cost which varies with range directly proportional to the block time variation. At zero range, and very short ranges, the unit costs (cost/airplane mile, or cost/

available seat mile) are very sensitive to the block time penalty or, in other words, the amount of time (and money) lost in getting the trip started. Thus, it is very important for a short haul air system to ensure that the block penalties are as small as possible, and conversely, it is important in estimating DOC to use correct estimates of this penalty. For V/STOL air systems, it will not be the same penalty as incurred by present airline systems.

Figure III-8 shows the block time variation for Los Angeles Airways. The block penalty is 1.5 minutes, which is accountable to time lost in climbing to 1500 feet cruise altitude. Thus, T_{am} and T_{gm}, the penalties associated with air maneuvering, and ground taxiing are zero or very small and discussions with the operating personnel indicate their concurrence. Similar discussions with other scheduled helicopter carriers agree with this conclusion. There is no traffic problem at present levels of frequency. Therefore, for the VTOL aircraft in this report, the values of T_{am} and T_{gm} are zero and this gives a block time penalty of the order of 1.5 minutes similar to Figure III-8.

The STOL aircraft does not have any operational experience, and a reasonable estimate of the block time penalties must be made. It is reasonable to expect some reduction from present airline experience, but since there will be air maneuvering associated with landing patterns, and maneuvering after takeoff to start the trip, and also ground maneuvering associated with taxiing to and from the runway and loading gate, the T_{am} and T_{gm} values will not be zero. In this report, T_{am} has been taken as four minutes which assumes a smaller landing pattern and the ground times for taxiing are six minutes to and from the runway.

Crew

A minimum operating crew consisting of one pilot and one co-pilot has been assumed throughout. One steward or stewardess working in the cabin is accounted for under indirect costs. All factors for a domestic operation are used. Until quite recently the minimum operating crew complement of commercial transport vehicles could consist of two pilots as long as the gross takeoff weight of the vehicle was below 80,000 pounds. The new ruling (F.A.R. 121-Change Number 3) allows manufacturers to exceed this weight, and retain the two man crew, as long as safe handling can be demonstrated satisfactorily. It is fair to assume that the V/STOL vehicles of this study will not require more than two operating crew members.

Fuel and Oil

Fuel has been taken as JP4 at 0.11 dollars per gallon and 6.5 pounds per gallon, and oil at six dollars per gallon and 8.1 pounds per gallon.

The fuel reserves and flight profile are as described for each vehicle on pages II-26 and II-27.

The trip length in statute miles is one of the parameters which is varied between 10 and 500 miles.

Insurance and Injuries

The standard ATA value of 4% of the aircraft cost per year has been taken for aircraft insurance rate, and .00087 dollars per aircraft mile for public liability and property damage rate.

Direct Maintenance

Standard ATA values of labor rate ($3 per hour), aircraft and engine labor man hours and materials cost per block hour have been taken.

The number of engines used in the computations is straightforward in all cases except for jet lift. In this latter event, since the lift engines operate only during the takeoff and landing phases, and since the TBO of the lift engines may differ from that of the cruise engines, account has been taken of this in a specific computer program written for jet lift. Under this cost heading, all costs for the lift engines are directly related to their time of operation. This is expressed by a variable ratio RA, where

$$RA = \frac{\text{Time of operation of lift engines}}{\text{Block Time}}$$

The values of RA are outputs from the vehicle design computer programs and all lift engine labor and material costs are multiplied by this factor.

Although their operating time is less than block time, the TBO of the lift engines is likely to be appreciably less than that of the cruise engines for many reasons, such as more frequent thermal cycles, lighter construction techniques, etc. Therefore, a variable parameter K has been introduced into the jet lift program where

$$K = \frac{\text{TBO of cruise engines}}{\text{TBO of lift engines}}$$

Thus where costs are dependent on TBO of engines, the lift engine costs are factored by K which has values ranging from 1.0 to 12.0, the base taken as 10.0.

Engine overhaul period (cruise engines in the jet lift case) is a variable ranging from 1,100 to 6,000 hours between overhauls, with 4,000 as the base.

The total direct maintenance cost plus applied burden are multiplied by a maintenance cost factor, Z, ranging from 0.5 to 10. The manner of arriving at the figure appropriate to each vehicle is explained as follows:

a) For the helicopter it has been shown that with current technology, the ATA formula will estimate the maintenance costs of the helicopter for all systems common to those of a conventional jet aircraft.

In the example used (Tables III-2,III-3), the actual cost of such common items is $98.43 per hour. The associated rotor and transmission costs are $16.85 per flight hour, that is, 17% of the former. But in fact this cost for transmission and rotor is somewhat lower than it should be since it does not include the cost of overhaul of those items which are now retirement items, and, therefore, capitalized. Consequently, for future predictions, transmission and rotor costs will be raised to the order of \$20 per flight hour.

Furthermore, helicopter turbine engine costs are tending to decrease, as discussed on page III-20, so that assuming "power by the hour" drops from \$27.5 to \$13 per flight hour per engine, this would decrease the figure of \$98.43 to \$69.43 per flight hour.

Therefore, the ratio of (Cost of Transmission and Rotor/ Total Maintenance Cost - minus rotor and transmission) is approximately $\frac{20-}{69.43}$ or 0.29. In this report, a value of Z of 1.3 has been taken as a reasonable estimate for maintenance cost factor for helicopter designs. Further work is necessary to establish realistic rotor and transmission costs based upon direct examination of current actual costs.

b) For the jet lift, there are no extraneous maintenance systems and the number of lift engines and their manner of operation is already accounted for using K and RA by the special jet lift program DOC computer. The maintenance cost factor is, therefore, 1.0.

c) Pitch control for the tilt wing aircraft is obtained either by monocyclic pitch on all propellers, or by a tail rotor. In addition propellers are interconnected by cross shafting and gearing so that the extraneous systems may be likened to those of a helicopter and a maintenance cost factor of 1.3 applied.

d) The maintanence cost factor for the STOL is reduced to 1.1, based on the relatively low power cross shafting.

Depreciation

Standard ATA figures of 15% residual value of airframe, engines, propellers, airframe and engine spares have been taken. Electronic equipment to the value of $150,000 is fully depreciated over five years to allow for the cost of the all weather system discussed in Section VIII. This depreciation implies replacement rather than repair, hence no additional maintenance cost has been added, over and above the normal weight factor, for maintenance of the automatic control equipment. Airframe spares are assessed at 10% of the empty airframe cost, and engine spares at 50% of the total engine cost with a spare parts price factor of 1.5 for engines only. Depreciation period is a variable ranging from 10 to 15 years, with 12 as a base.

Utilization

Utilization is a variable parameter ranging from 1,000 to

5,000 hours per year. A value of 3,000 has been assumed as a base. This latter is entirely feasible, even with very short haul, frequent stop service as discussed in Part IV.

Cost of Airframe and Engines

To estimate the airframe price, the costs are separated into production costs and development costs. The production cost of airframes has been based on a standard learning or experience curve using the following relationships:

$$C_n = C_o\, n^{-p}$$

where C_n is the cost of the n^{th} vehicle and p has the value of .234 for an 85% learning curve, that is, for the cost decreasing to 85% each time the production run is doubled. The initial value C_o has been chosen as a result of the analysis of costs for several existing aircraft, both fixed wing and rotary wing.

From the above relationship, it is easy to obtain the average cost over a sufficiently large continuous production run of N vehicles as

$$C_{AV} = \frac{1}{N} \int_{0}^{N} C_n dn = \frac{N^{-p}}{1-p} \; C_0$$

The development costs are more difficult to identify particularly in view of the large number of changes at discrete production runs (block changes) normally incorporated during the life of an aircraft system. However, analysis of several typical systems have indicated development costs of about \$2,000 per pound for the initial procurement with the total development costs over the life of the vehicle being closer to \$5,000 per pound, which would allow for incorporation of changes during the production run and the sustaining engineering required to develop a reliable low maintenance vehicle. It is assumed that the aircraft used in this study will have been fully developed by the time commercial service is inaugurated and that all these development costs are absorbed into the cost of the vehicle.

Although the number required for the transportation network used in this study is of the order of 100, an average production run of 300 was taken since it is more than probable that the vehicles developed for this system would also find wide usage elsewhere. Parametric analyses have been conducted using production runs varying from 100 to 5,000 as discussed in Part II. The base value of airframe cost, using a run of 300, and $5,000 per pound (AMPR) developments cost, is $68.2 per pound.

The engine cost has been based on an analysis of the costs of several existing engines. Since the production runs on engines are generally much larger than for airframes and the same engine is used in several different vehicle configurations, no learning curve or development costs have been assumed. Rather it has been found that an average cost of $40 per horsepower is representative of present day turbo-shaft engines and $15 per pound of thrust for jet engines. On present day engines these numbers correspond to about $100 per pound of engine for the turbo-shafts and $50 per pound of engine for the turbo-jets. For the advanced engines used in this study, it was conservatively assumed that the cost per horsepower would remain constant rather than the cost per pound. Since the assumed thrust to weight ratios are predicted to improve by a factor of 3, this results in engine costs of $300 per pound of engine for the shaft engines and $150 per pound of engine for the jet engines. It is possible that engine costs will follow more closely a weight rather than a power relationship which would permit using the present day values quoted above. This would imply that the improvement in specific thrust or power would not be obtained at the expense of complexity or highly refined design.Such an assumption is certainly true for the lift engines where the weight reduction is obtained by a simplification in design, the elimination of extra turbine stages and a reduction in compressor stages, fuel consumption not being as critical an item in these engines. Consequently, the figure of $150 per lb. of engine has been used also for the lift engines, whose specific weight is about half that of the cruise engines.

The effect of these conservative engine weight estimations on the DOC is shown in the parametric studies of Part II, Figure II-44. Clearly the assumption of engine costs is a critical one since these costs are reflected in depreciation, in the high cost of replacement parts in maintenance, and in aircraft insurance costs. This effect is particularly noticeable on the VTOL aircraft because of the large amounts of installed power and thrust. The importance of keeping engine costs low is obvious.

AREAS OF POTENTIAL DIRECT OPERATING COST REDUCTION

Operating Crew

Since a high proportion of the operation of an airbus system is takeoff and landing, where the multiplicity of functions calls for no less than two men, there does not seem to be any potential for reduction of crew costs by reducing crew size.

Salary levels for conventional aircraft crews tend to increase with the years. Furthermore, the complex makeup of the pay is the result of a long history of bargaining. Inauguration of a new airline service with VTOL aircraft could provide an opportunity to create an entirely new type of contract, with salary scales regulated to the skills required. Since crew pay represents some 20% of the total Direct Operating Cost, this is an area well worthy of further consideration.

Fuel and Oil

In this study the vehicles are designed to operate for minimum direct operating cost rather than minimum fuel consumption. This requires a specific fuel consumption with a fairly flat optimum over a wide range of operation. Further details of expected improvements are given in Part II.

To meet the same mission requirements, the fuel and oil costs of the jet lift are a much higher percentage of the total direct operating cost (48%) than for a helicopter (16%), and any improvement in Specific Fuel Consumption would bring proportionately greater returns.

Insurance and Injuries

The 4% insurance rate of the ATA formula agrees well with the industry average and is the result of a steady improvement in the safety record achieved by commercial operators throughout the world. It is conceivable that a well constructed flying program coordinated with the insurance industry and operated prior to full scale commercial airline service could establish a safety picture that would encourage application of the conventional aircraft rate to the V/STOL right from the start of service.

Maintenance

This is perhaps the most sensitive of the cost groups. For conventional aircraft, direct maintenance plus applied burden comprise about 33% of the total D.O.C. while for current helicopters this figure is greater than 50%. Fortunately, maintenance is also the one area where there is the greatest potential for cost reduction. The current helicopter engines, which cost around $30 per flight hour at the start of operation, are forecast to cost around $13 per flight hour in a few years, and this is an engine not specifically designed for a helicopter installation.

There are many places where concentrated effort and development could lead to valuable maintenance cost reduction.

The Design Stage

This is the most important single factor influencing maintenance costs. Bad design (and bad luck) breeds defects, premature removals, frequent inspections, low TBO's, modification programs, delayed or cancelled departures, reroutings or altered schedules, and finally, disillusioned passengers.

It has already been pointed out that during the design stage, the maintenance engineer with his experience of airline practices is as crucial to the excellence of the final product as is the aerodynamicist and the stress analyst. How often has weight been "saved" by the manufacturer only to be reinstated with a penalty in time, labor and materials, and probably weight, by the operator? Of what value is a beautifully designed gear train, if it needs lubricating once a day and the grease nipple is in a highly inaccessible location? Where is the advantage in using weight-saving magnesium alloy castings, if they will need frequent corrosion checks and probably early replacement?

Manufacturers of current jet equipment are well aware of the role that they play after an aircraft has been delivered. They are still part of the parentage, bearing responsibility for the behavior of the vehicle, and are concerned, therefore, that it shall operate safely and trouble-free. More and more terms such as "reliability" and "maintainability" creep into sales literature and specification guarantees. With the 737 still on the drawing board, Boeing has been forecasting that within 12 months from the start of commercial service the dispatch reliability would be at least 97%. This is no empty boast. It is based on careful analysis of the 727, the characteristics of the units in each system, their number and mode of operation, and the history of their defects. (Ref. III-1). Whenever analysis has revealed any shortcomings in design, a new approach has been ordered, and money spent in development. It was possible, in this manner, to assess the total development investment to meet the 97% guarantee.

Whilst there is little doubt that the more time and money spent on development, the greater the likelihood of producing a low-maintenance cost vehicle, it is difficult to assess the absolute values of the investment to achieve specified reliability levels. This is clearly an area for further study.

Adequate pre-delivery testing, more particularly of the kind which approaches closest to the ultimate real operating conditions, is vital to low cost maintenance. Preferably it should be well ahead of the production run so that any modifications are installed prior to delivery. Continuous accelerated testing should proceed so that whatever corrective action may be required is available in good time for the material and inspection planners.

Component Lifetime

Most airline thinking, up to the present day, assumes that the majority of the removable components have wear out characteristics which are functions of time, i.e. hours of operation, and it has been customary for the regulatory authority to impose specific TBO's for each unit, allowing them to increase as experience builds up. Furthermore, the initial approved TBO has tended to be low to be "safe."

In fact, this policy has 1) tended to increase the exposure to infant mortality for units whose failure rate decreases with age; 2) prevented the full exploitation of those units where failure rate characteristic is constant with time; and 3) not prevented "premature" failures of complex units.

Since a substantial portion of aircraft parts have failure rates independent of age, there is no impairment of safety in not imposing a time limit, (Ref. III-2) and there is a very definite cost saving.

Even where the failure rate increases with time, it is not necessarily more expensive to replace at failure than schedule a planned removal, since the latter implies a recording system and some organization to administer the removals.

United Air Lines is presently conducting a number of programs designed to find a more rational relationship between age and reliability, (Ref. III-3). Some extension of these schemes should be a part of the maintenance schedule to be set up for the V/STOL vehicle. In brief the programs are as follows:

Reliability Controlled Overhaul (RCOH). Units which qualify for this scheme have demonstrated that their reliability does not deteriorate with time (see Figure III-3). They are allowed to remain in operation until they fail. Most electronic equipment falls into this category.

United Air Lines claims a saving of 500 scheduled overhauls a year from just five selected components, conservatively estimated at $75,000 per year.

(Taking a figure of $.05 per flight hour for overhaul of a single electronic unit, a utilization of 3,000 hours a year, and a conventional overhaul requirement of 12 months TBO, the cost saving would be

$$\$0.05 \times 500 \times 3{,}000 = \$75{,}000 \text{ per year).}$$

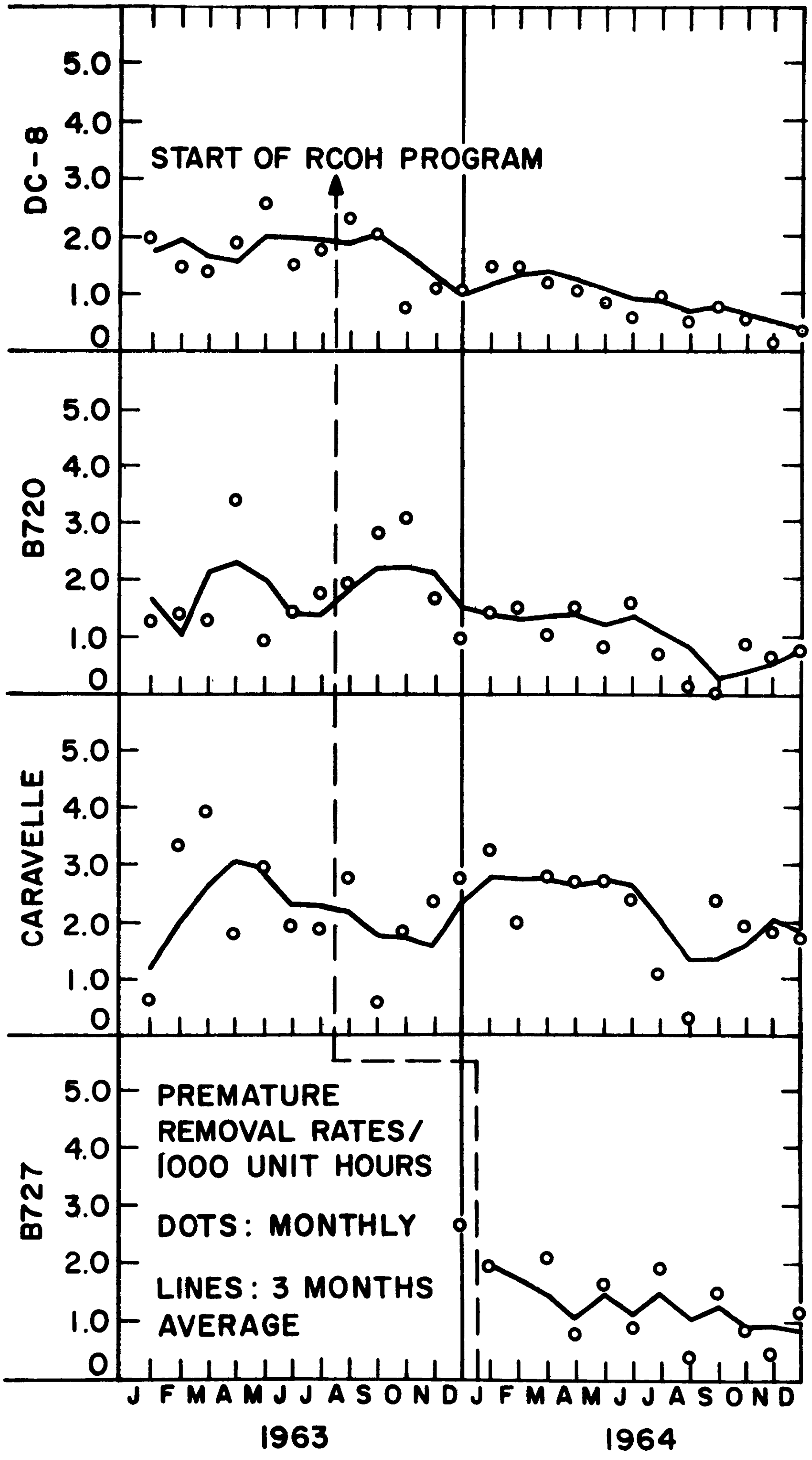


FIG. III-3 TRANSPONDER ATC

It is true that UAL had historical data available before assuring themselves that this was the correct approach. In the case of a new V/STOL machine this background would have to be accumulated during the pre-delivery testing period so that the unit could at least be classified as falling into a category suitable for such life development at the start of commercial service.

Test and Replace as Necessary (TARAN). This program is ideally suited to systems (as opposed to individual components) whose performance is capable of measurement *in situ*. UAL chose the hydraulic system for its pilot scheme which involves:

a) Accurate checking of internal leakage rates of subsystems, with the ability to isolate individual components and replace them if necessary.
b) Shop testing of prematurely removed components, verifying their non-serviceability, and recording the symptoms.
c) Recording premature removal rates.
d) Precautionary removal and inspection of components with low unscheduled removal rates.
e) Basing pump and system return filter inspections on the condition of the case return filters.

Since the start of the program UAL claims to have saved:

a) 114 scheduled component overhauls;

b) removal during aircraft overhaul of 1167 hydraulic components; and

c) 1,000 manhours per aircraft overhaul.

In addition, the premature removal rate of hydraulic components has decreased on TARAN-overhauled aircraft.

The savings from manhours alone amounts to $875 per aircraft per year. (Based on a 12,000 hour aircraft overhaul period, 3,000 hours utilization and $3.5 per manhour.)

Component Reliability Program. To qualify for this program the units have:

a) to be complex;

b) to be costly to overhaul, thereby ensuring that savings will cover the added expenditure of administering the program; and

c) to show little or no change in failure rate with time so that there is no risk of sudden fleet-wide failures.

The units in this scheme do not have fixed TBO's. Instead, their case histories are constantly being monitored to ensure no change in the local probability of failure with age.

Every month highest time sample units are removed, thoroughly checked and tested, and then overhauled.

In the case of the 720 B generator, for example, the units have gone from a fixed TBO of 2,000 hours to lives of 5,100 hours and up, in the span of 16 months, with premature removal rate remaining substantially constant. (See Figure III-4.)

Engines are excellent models for this scheme. (See Figure III-5). Firstly, one overhaul saved is of the order of $50,000. UAL has shown that at the rate of 34,000 engine hours per month, just 400 hours increase in TBO from 3,000 to 3,400, has saved 1.2 overhauls per month. Another way of looking at the savings is to note that with a fleet of 29 four-engined aircraft, and 25 spare engines, the total hours not requiring overhaul through this time extension is some 56,400, equivalent to 19 overhauls at 3,000 hours TBO, a gross saving of about $950,000.

Secondly, with conventional time extension programs, the monthly overhaul costs are initially high due to the high volume of scheduled overhauls per month. The overhaul facilities and spares holding have likewise to be sized to meet this volume. Later on, as TBO's increase, the spares and facilities are greater than is required. This heavy initial investment is eased with the Component Reliability Program.

Referring to Figure III-6; Line ABC represents an optimum TBO presumed known prior to the start of service. Hence overhauls begin at date A and costs remain constant thereafter. Line

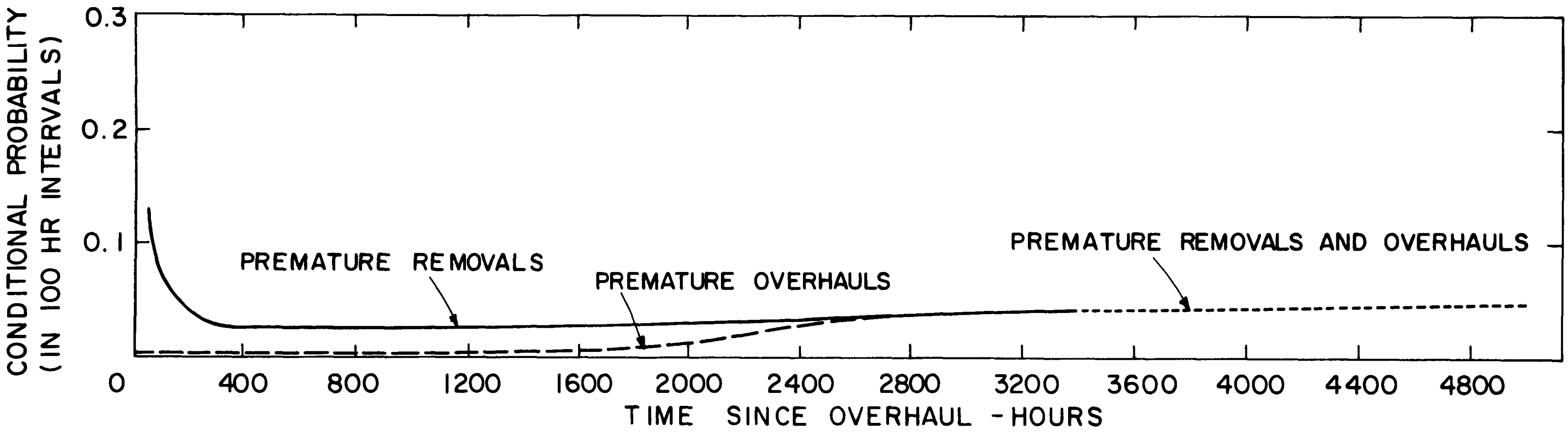


FIG. III - 4 CONDITIONAL PROBABILITY OF FAILURE - BOEING 720 GENERATOR

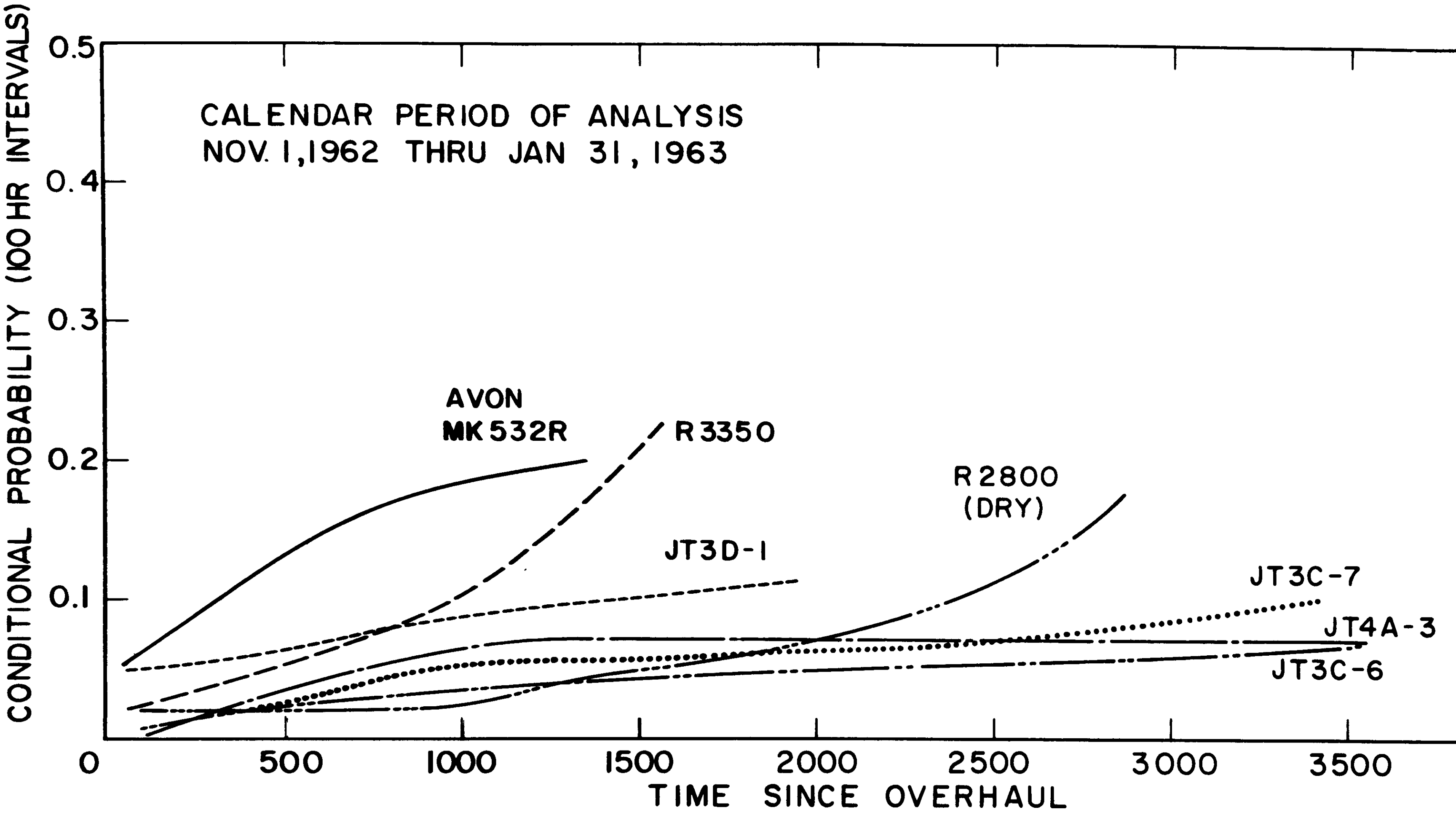


FIG. III-5 CONDITIONAL PROBABILITY OF PREMATURE REMOVAL MAJOR PISTON AND TURBINE ENGINES

DE represents the usual practice of starting overhauls soon after the start of service with initially low TBO's slowly building up to the optimum at E. Line FGHEC represents what is possible with the Propulsion System Reliability Program. Areas under each curve represent the total overhaul cost from the start of service. Hence the cross hatched area represents the savings achieved by adopting an accelerated TBO extension program instead of that normally conducted.

Component Reliability Engineering Evaluation Program (CREEP). The purpose of this scheme is to reach a point in evaluating components where removal from an aircraft is governed not by some arbitrary fixed TBO, but by failure to meet a realistic functional test *in situ*. And complementary to this is a policy which returns the component to "zero time" service not by overhaul, but by rectifying the immediate cause for removal and performing the minimum servicing work and replacement of time-related parts.

This is still valid for components showing no variation of conditional probability of failure with time (for example, III-4) such that the reliability after overhaul is the same as it is at any other time. Consequently, why overhaul when a less costly method returns the component to serviceability with no loss of reliability? Illustrative of this is Figure III-7, where it is shown that the same unit, whether overhauled (circled data) or repaired and functionally checked (dots) does not produce an increase in premature removal rate and in fact shows a slight decrease.

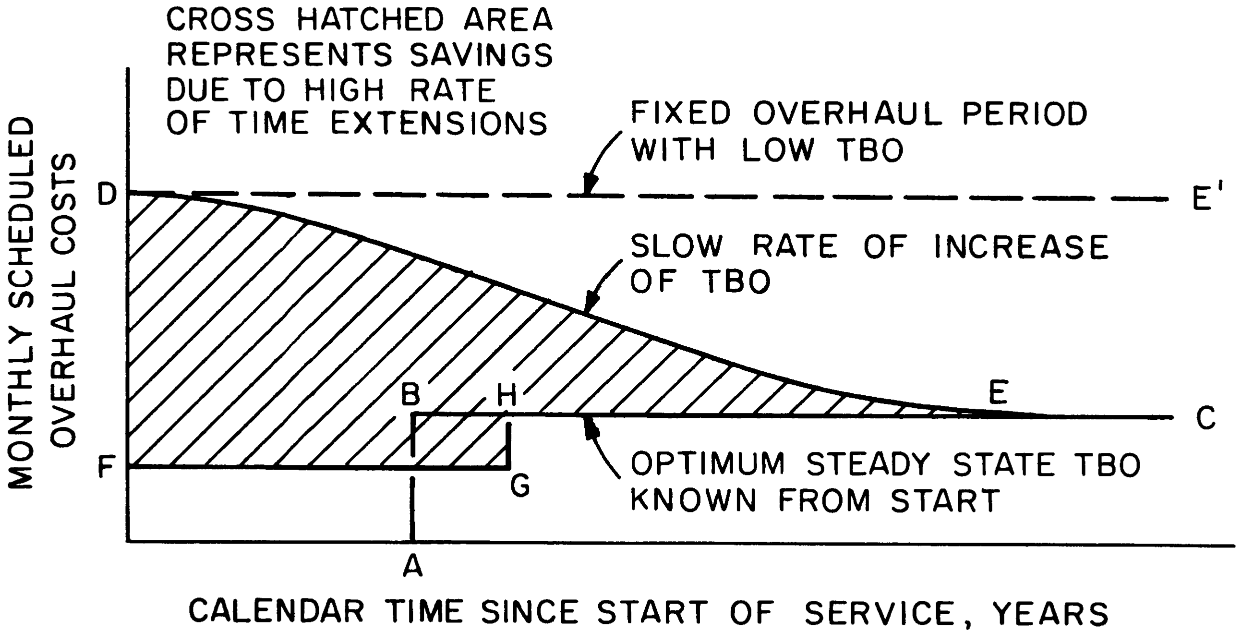


FIG III-6 SCHEDULED OVERHAUL COST COMPARISON

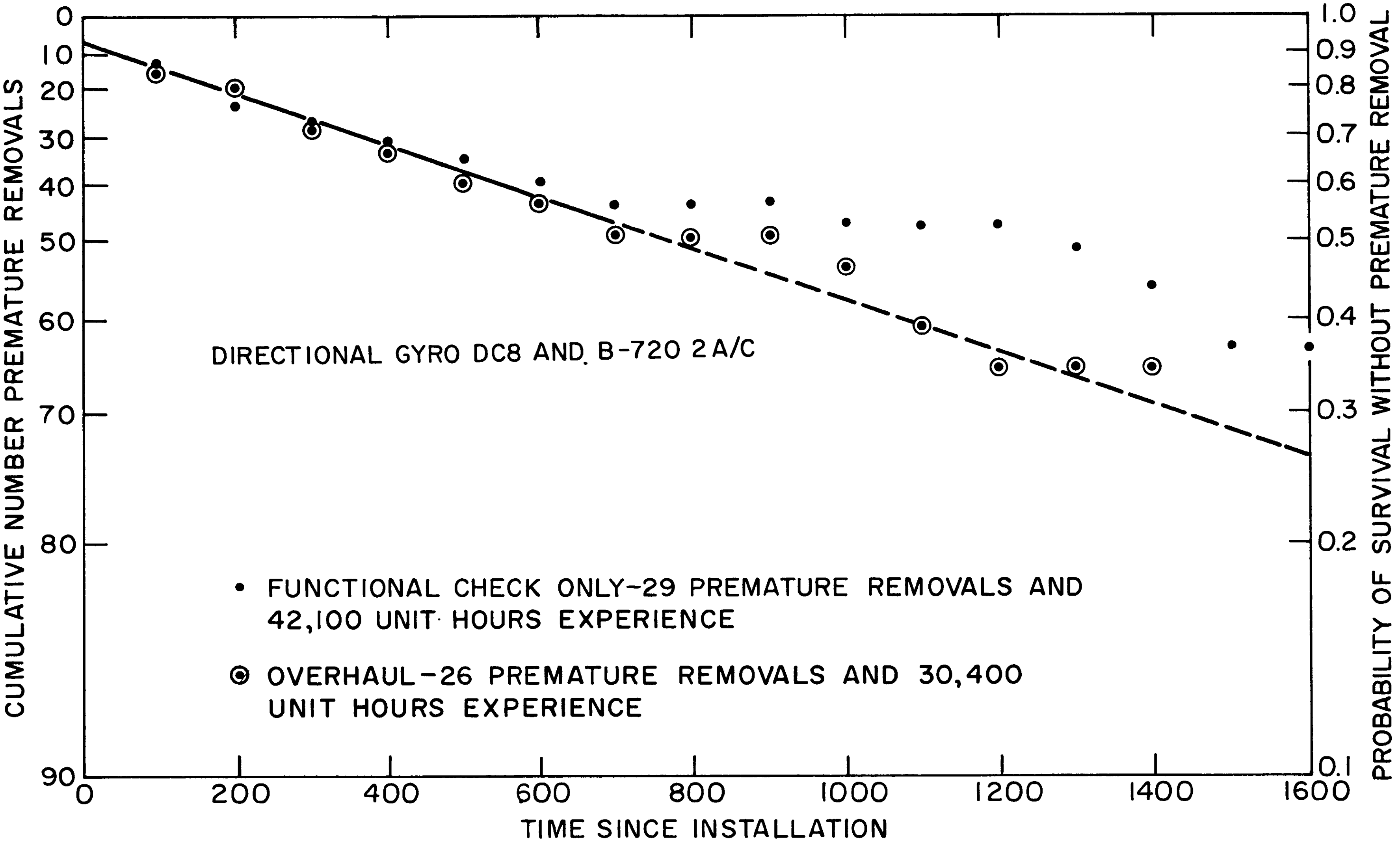


FIG. III-7 PREMATURE REMOVALS (PER 100 INSTALLED UNITS)

This specific evaluation technique being used by UAL at present is costly, as it involves the participation of many parties, the careful and detailed external inspection, functional check, disassembly, and inspection of parts, and summing-up discussion to finalize the next stage. Presumably, when this scheme becomes routine it will be less involved, and will serve as a pointer to what can be done with future aircraft.

"Black Box" Maintenance

Much of the success of a high utilization VTOL operation depends on dispatch reliability. With a large fleet size it is possible to some extent to provide a back-up vehicle through scheduling, but this must remain a secondary device. The primary means of keeping the vehicles flying must be through the techniques of rapid "trouble shooting" and equally rapid rectification of faults. Airborne equipment is now under development which monitors system operation and locates trouble spots. There are also ground rigs capable of checking out aircraft systems. If the aircraft systems were designed around the "black box" principle, replacing a suspect unit would simply involve removing one black box and installing a serviceable one in its place. This is undoubtedly fast. However, test equipment of this kind tends to be expensive, and whether it would be economically worthwhile would depend upon the basic reliability of the vehicle. The desirability of such equipment is weighted by the VTOL airbus mode of operation. Since the aircraft must have all weather capability, and will be taking off and landing frequently, it will require reduncancy in some systems, implying greater complexity, and therefore potentially lower overall reliability. This is an area worthy of further study.

Potential Reduction in Maintenance Costs For 1980 Advanced V/STOL Aircraft

An estimate has been made of the cost savings that might be achieved by utilizing the techniques discussed in the preceding paragraphs. (This is summarized in Table III-4.) The datum for comparison is the Boeing 720 B, which now has a maintenance cost factor of 1.0, and which demonstrates close agreement between actual direct maintenance costs and those predicted by the ATA formula.

A. Since a high value of $5,000 per pound of airframe for development costs has been used, it is meant to ensure that the vehicle enter service with a very high reliability. Thus it is reasonable to assume that unscheduled maintenance should be significantly cut. Taking current unscheduled maintenance to be 25% of the scheduled (this is conservative), and reducing this by 50% gives a reduction of 12.5% on total maintenance cost.

B. Again, because of the superior reliability, and design for maintenance, there is good reason to expect the period between checks to increase. Taking it to be double, without any increase in the inspection content, and assuming inspection is one half of the labor involved, gives a reduction in labor cost of 25%.

C. With most of the modifications resulting from service experience on earlier models introduced by the manufacturer prior to aircraft delivery, the number of changes required to be introduced by the operator should significantly drop. A 50% reduction has been assumed, which, applied to the current ratio of modification cost to total cost gives a reduction of 3% in total labor cost and 5% in total material cost.

D. Electronic units are assumed to be off time control, and this has been translated into a conservative reduction of 15% on total maintenance costs for such systems.

E. Systems which can be maintained in a manner similar to the TARAN program for the hydraulic system are given credit for a potential reduction of 5%.

F. For those systems where the components will have a virtual TBO, it has been assumed that this will be much higher than current levels, and accordingly 15% reduction in total maintenance costs is meant to account for this improvement.

Potential Maintenance Cost Reductions on Current Costs

	Basis for Reduction	% of Total Labor Cost Reduced	% of Total Material Cost Reduced
A	Assume ratio of Unscheduled/ Scheduled maintenance reduced by 1/2. Present ratio taken as 1/4	12	12
B	Double period between inspections and take inspection manhours as 1/2 of labor.	25	--
C	Reduce modifications by 1/2	3	5
D	For <u>Electronic Units</u> - no fixed overhaul time. Assume 15% reduction in actual overhauls required. (If D applies, F does not.)	15	15
E	For <u>Systems</u> like <u>Hydraulics</u>, capable of <u>in situ</u> testing, assume 5% reduction.	5	5
F	Where lifetime is applicable, higher than current values are obtainable. Assume 15% reduction. (If F applies, D does not.)	15	15
G	Rectification acceptable instead of overhaul. Assume 5% reduction	5	5
H	"Black Box" maintenance should cut labor cost. Assume 2%.	2	--

NOTE: Engine life accounted for in main DOC Computer program through TBO.

TABLE III-4

G. Adopting a policy of performing the minimum to achieve serviceability, rectification will often replace overhaul, and a 5% saving has been taken.

H. "Black Box" maintenance helps reduce labor for those systems where this technique is possible, and in such cases 2% reduction has been assumed.

Applying these reductions wherever appropriate to the labor and material portions of the 720 B aircraft system cost breakdown shows that potential direct maintenance costs of a vehicle similar to the 720 B, designed in accordance with the premises outlined in this study for the 1970-1980 decade, should be 0.66 of current costs.

For the purposes of this study, therefore, the following potential maintenance cost factors have been assumed for advanced technology vehicles in the 1980 and beyond period.

Vehicle	Maintenance Cost Factor	
	Current Value	Projected Value
Conventional Jet	1.0	0.7
Helicopter	1.3	0.9
Tilt Wing	1.3	0.9
STOL	1.1	0.8
Jet Lift	1.0	0.7

Depreciation

The depreciation period of an aircraft is either a self-imposed arbitrary figure, or a very real externally imposed figure, variously dependent on the economic market in which the fleet is operating, the political environment, the technical state-of-the-art, the airline management philosophy, and the aircraft manufacturer's decisions.

The DC-3 has had a very slow real depreciation period because, until quite recently, there were not competitive aircraft. This was not because technical knowledge was lacking, but because no manufacturer had decided to build one. On the other hand, the DC-7 had a very rapid real depreciation because it had highly competitive jet equipment coming off production lines at the same time as itself. The current jet equipment has every chance of reaching 12 to 14 years realistic depreciation without becoming obsolete because the next competitive jump is to a supersonic transport, forecast for the 1975 period.

One of the problems associated with a VTOL airbus is that it will be an early generation commercial vehicle, pioneering the path for developments which could gradually lead to superior machines akin to the steady advance from early twin piston-engined transports to the subsonic four-engined jet transports of today. This could, in an open market situation, produce early artificial obsolescence.

The question is: would it be an open market situation? The agency that will be controlling the airbus operation could, if it were without competition, establish its own realistic depreciation period. However, it may be argued that this would stultify progress, since healthy competition stimulates more rapid realization of an ideal machine. The problem would have to be judged on its economic merits. Introduction of VTOL service will in itself be a quantum leap forward in point to point travelling time. It would be more economical to concentrate on reducing the cost of this operation and improving its reliability through the normal forms of progressive modification action, rather than to sponsor early replacement by a newer aircraft, somewhat superior in speed and economy of operation.

III
CONCLUSIONS

1) ATA formula, while deviating in particular components from actual costs, still seems a very reasonable method of estimating DOC of jet transport aircraft.

2) The ATA formula can apply to V/STOL operations directly except for one major discrepancy - the maintenance costs of V/STOL vehicles where the major components which are not found in jet aircraft must be taken into account.

3) The VTOL maintenance direct operating costs can be estimated using a maintenance system cost breakdown based on equivalent aircraft system costs for similar systems, and estimates based on actual systems costs for those systems not found in fixed wing aircraft.

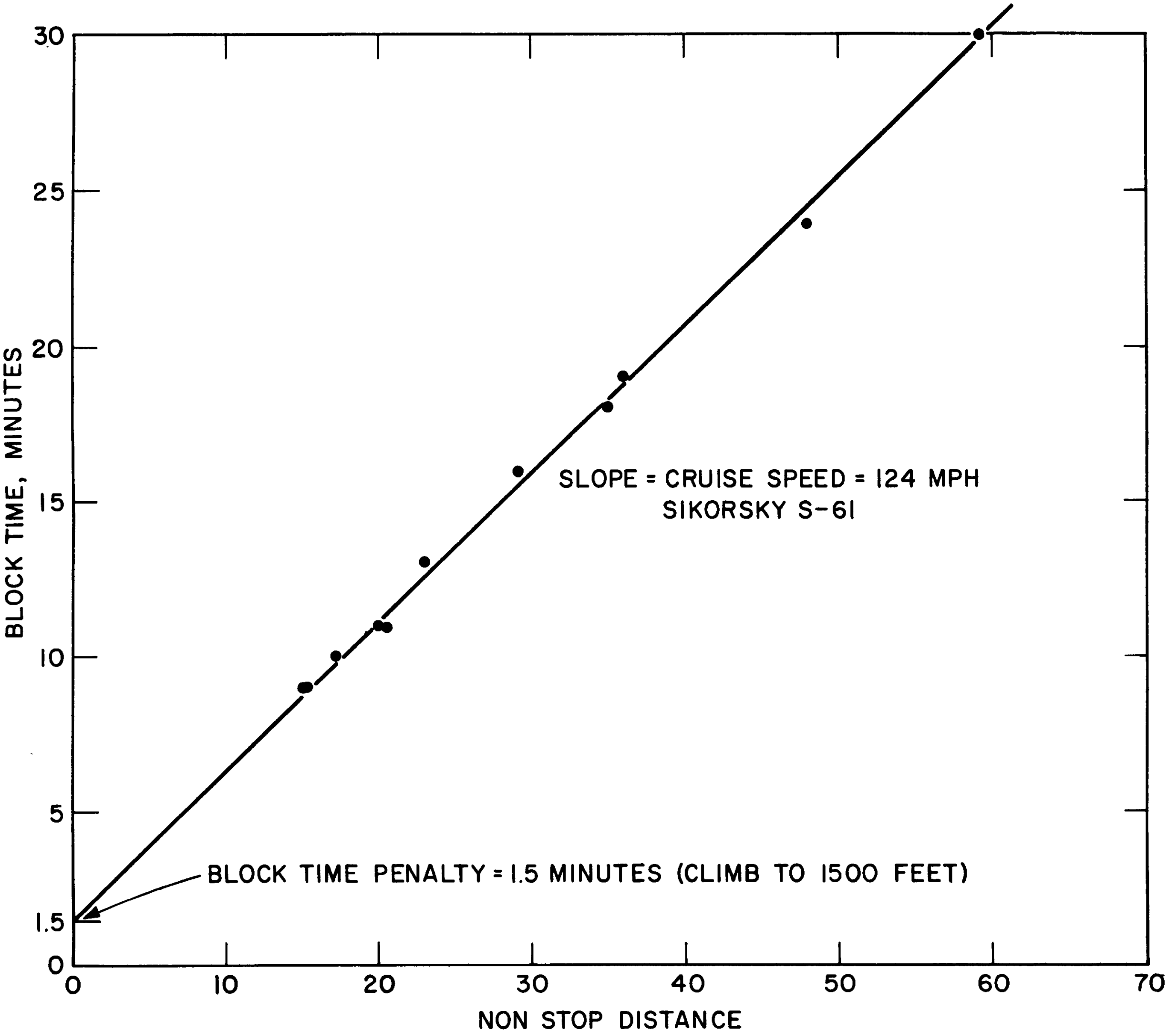


Figure III-8 BLOCK TIME vs. DISTANCE, LA AIRWAYS 1964

III
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2 M. Kamins and J.J. McCall, Jr., "Rules for Planned Replacement of Aircraft and Missile Parts," Rand Corporation Memorandum RM - 2810 - PR, November 1961.

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PART IV

TRANSPORTATION SYSTEM STUDIES

TRAVEL DEMAND

IV

TABLE OF CONTENTS

INTRODUCTION

In order to make the study of a possible 1980 air transportation system meaningful, some estimate of the passenger demand between northeast corridor city centers was needed. The system of routes to be served; the number and size of the vehicles needed; the terminal facilities; the size of the computation and data processing system; and the frequency of service, among others, are passenger demand determined.

A simple computer model of demand,applying to all routes, was deemed necessary for two major reasons. First, the actual routes to be served will be chosen by a network optimization computer program, requiring as input demands between all cities in the network--too large a matrix to be manually produced. Second, various shapes of demand functions might be tested quickly to judge the effect of varying fares or services and as a check of the sensitivity of the final network and total system characteristics to demand estimations.

The rationale followed was to examine briefly a model for total transportation demand over varying distances and then to modify this model so that only air travel in this system was represented.

NORTHEAST CORRIDOR AIRBUS TERMINALS

Terminal Location	Code designation	1980 Population	Passenger Originations Per Day
MAJOR TERMINALS			
Boston, Mass.-Logan Airport	BOS	1,478,500	2030
Boston, Mass.-in or near downtown	BOC	1,508,800	2060
New York, N.Y.-John F. Kennedy International	JFK	2,818,800	2220
New York,N.Y.-LaGuardia Airport	LGA	3,801,600	2970
New York,N.Y.-Wall Street Heliport	JRB	1,097,000	850
New York, N.Y.-Pan American Building	NYC	1,701,700	1250
Newark, N.J.-Newark Airport	EWR	1,933,800	1490
Philadelphia, Pa.-Philadelphia Airport	PHL	2,413,900	2140
Phildelphia, Pa.-downtown on the river	PPA	3,653,100	2990
Baltimore, MD.-Friendship Airport	BAL	757,700	940
Baltimore, Md.-in or near downtown	BMR	1,850,900	2120
Washington, D.C.-Washington National Airport	DCA	1,162,000	1550
Washington, D.C.-downtown	WAS	1,801,956	2250
OTHER TERMINALS			
Portland, Me.-Portland Airport	PWM	136,000	200
Manchester, N.H.-Gernier Airport	MAN	111,700	170
Lawrence-Haverill, Mass.-Lawrence Airport	LAW	198,400	260
Fitchburg, Mass.-Fitchburg Airport	FIT	100,000	80
Pittsfield, Mass.-Pittsfield Airport	PIT	90,800	120
Worcester, Mass.-Worcester Airport	WOR	368,100	500
Brockton, Mass.-Brockton Airport	BTN	232,900	300
Providence, R.I.-Providence Airport	PVD	941,500	1200
New Bedford, Mass.-New Bedford Airport	NBD	146,100	210
Springfield, Mass.-Springfield Airport	SPR	636,100	750
Hartford, Conn.-Rentschler Airport	HFD	693,700	760
Hartford-Springfield - Bradley Field	BDL	182,000	710
Waterbury, Conn.-Waterbury Airport	WBY	250,300	310
New London, Conn.-New London Airport	GON	254,700	290
New Haven, Conn.-New Haven Airport	HVN	416,600	410
Bridgeport, Conn.-Bridgeport Airport	BDR	499,600	460
Norwalk, Conn.-Southwest of downtown near the water	NWK	196,800	160
Stamford-Greenwich, Conn.-Between Stamford & Greenwich near water	SGC	796,200	630
New York, N.Y.-Teterboro Airport	TBO	1,023,200	760
Long Island, N.Y.-Mitchell AFB (abandoned)	MIT	1,627,200	1250
Islip, Long Island, N.Y.-MacArthur Field	ISP	417,700	350
East Quogue, Long Island, N.Y.-Suffolk County AFB	EQU	292,200	310
East Hampton, Long Island, N.Y.-Airport	EHM	126,100	130
Scranton, Pa.-Scranton, Airport	AVP	194,200	210
Wilkes-Barre, Pa.-Wilkes-Barre Airport	WBA	271,900	320
Allentown, Pa.-Allentown Airport	ALL	621,700	580
Reading, Pa.-Reading Airport	REA	319,500	320
Harrisburg, Pa.-Harrisburg Airport	HAR	431,300	580
Lancaster, Pa.-Lancaster Airport	LAN	391,900	420
York, Pa.- York Airport	YRK	329,900	370
Trenton, N.J.-Trenton Airport	TRE	357,900	290
Atlantic City, N.J.-Atlantic City Airport	ACY	239,600	240
Wilmington, Del.-Wilmington Airport	WIL	631,200	660
Washington, D.C.-Dulles Airport	DUL	776,900	1070
Richmond, Va.-Richard E. Byrd Flying Field	RIC	633,000	880
Newport News-Hampton,Va.-Civil Airport	PHF	570,500	820
Norfolk, Va.-Norfolk Airport	ORF	972,500	1430

TABLE IV-1

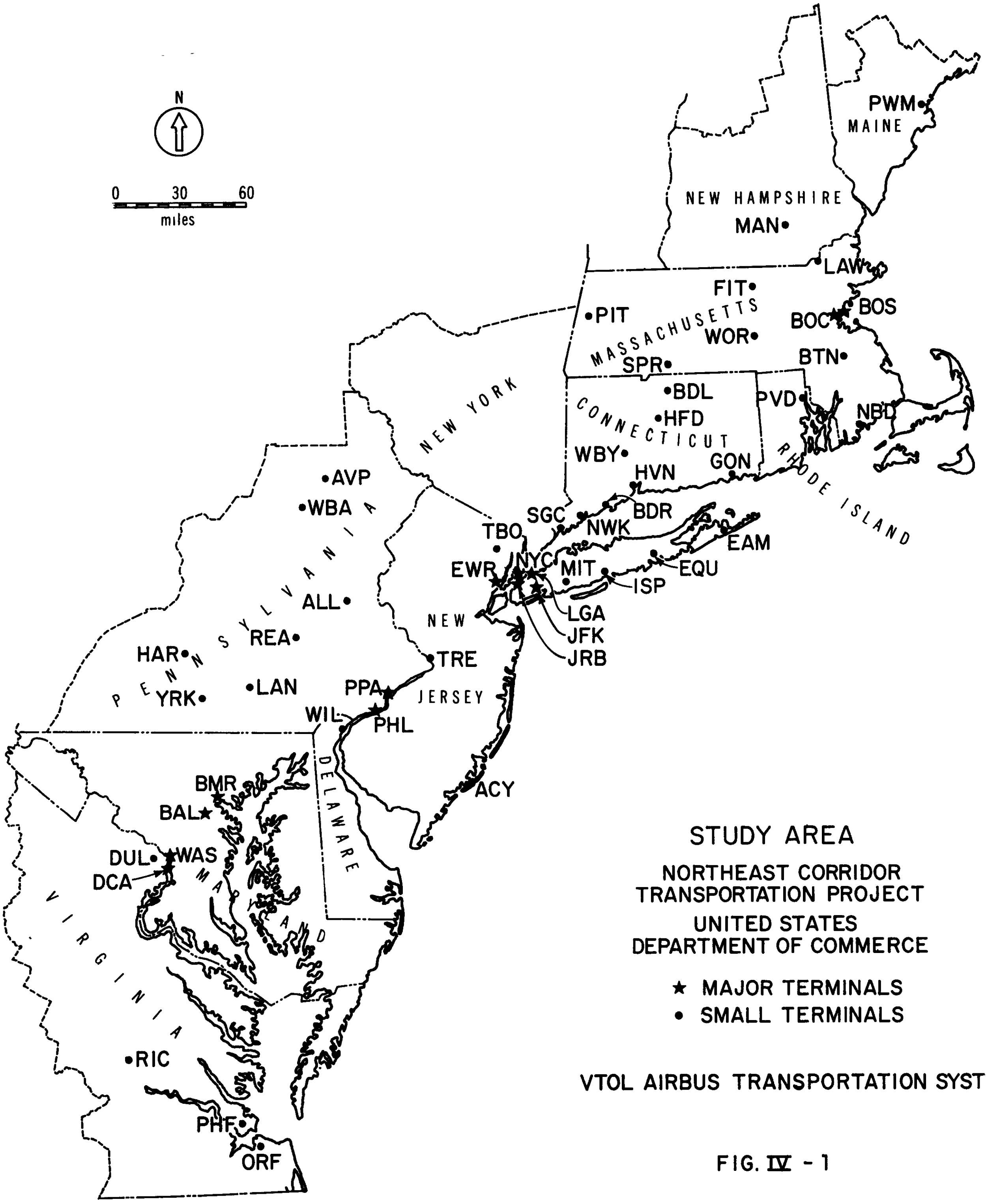
Terminal Locations

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 (Ref. IV-1) suggested 26 metropolitan areas to be served. These were taken and other cities added on the basis of population size and density. In the fifty terminal locations are represented 38 Standard Metropolitan Statistical Areas. (Ref. IV-2.) The locations, abbreviations (designations), predicted 1980 populations, and passenger originations per day at each point are given in Table IV-1. A map of the locations is presented in Figure IV-1.

Nautical Mile Distances

Since the demand estimation model was to be based in part on the distance to be travelled, a program was written that computes the nautical miles distances between all terminals in the network, given the latitude and longitude of each site.



STUDY AREA

NORTHEAST CORRIDOR
TRANSPORTATION PROJECT

UNITED STATES
DEPARTMENT OF COMMERCE

★ MAJOR TERMINALS
● SMALL TERMINALS

VTOL AIRBUS TRANSPORTATION SYSTEM

FIG. IV - 1

Populations

Populations were determined from 1960 Bureau of Census breakdowns of the Standard Metropolitan Statistical Areas. No consideration was given to existing ease of transport to the various terminal sites; the populations used reflected locations near the terminal only.

These figures were expanded linearly (rather than geometrically) at their individual 1950-60 rates of growth to a figure for 1980. Consequently, they may represent conservative estimates.

Although airport population data was gathered, it was deemed too difficult to estimate the number of these passengers who were leaving the corridor, and therefore, might use the corridor system as transport to the airport.

THE TRAVEL DEMAND MODEL

Bo. K. O. Lundberg (Ref. IV-3) suggests that the total passengers vs. distance curve for all modes follows the "gravity model:"

$$P_{ij} = K \frac{P_i P_j}{d_{ij}^{c+1}}$$

where:

P_i = population using location i
P_j = population using location j
P_{ij} = passengers between i and j
d_{ij} = distance between i and j
K = constant
C = constant (about 1.2)

D.M. Belmont (Ref. IV-4) finds that this general curve holds well for airline travel over 400 miles under comparable service conditions, but that it is not as distance sensitive. His value for $C + 1$ was about 0.4.

Therefore, we may accept the gravity model over the longer distances. The critical problem for the 1980 system, however, is that a predominance of the corridor flights will be in the short range, mainly centered around 100 miles, and no research has been performed considering distances of this magnitude and a system of this character.

It is felt that with the basic system including only 50 terminals, the very short range (1-20 miles) trips will continue to be handled by other modes, mainly the automobile. From there, however, a gradual buildup of passenger use should occur until a meeting with a gravity model curve at about 200 miles range.

This rationale suggested a gravity model modified by an exponential function at low ranges. The model chosen, therefore, has the form:

$$P_{ij} = \frac{KP_iP_j}{d_{ij}^{\alpha}} \cdot (1 - e^{-(Cd_{ij})^{\beta}})$$

where α, β, C, K are constants.

For the initial run, values of $C = .007$ and $\beta = 2$ were used as an estimate of the shape of the curve in the short range portion. This gave a median peak to the distribution at 200 miles distance. A further set of values has been chosen to study a distribution which peaks at 100 miles.

There are effectively only three points in the Corridor between which there exists a reasonably comparable system of transportation to that proposed for 1980. This is the frequently run "air shuttle" between Boston-New York-Washington. However, when other selected points in the Corridor were plotted (using present CAB origination and destination figures and present populations), it was found that these three are definite exceptions. Figure IV-2 shows several of these city pairs, along with the predicting model for $K = 3 \times 10^{-7}$ and $\alpha = 0.4$. The results gave 16.7 million passengers per year on the 1980 air system.

This demand would represent a predicted total air travel with a substantial increase in the air proportion of short haul travel under 300 miles. It is not a prediction, but rather a demand model generated to allow some network analysis.

NE CORRIDOR DEMAND FUNCTION FOR AIR TRAVEL
(with actual 1962 CAB O&D figures)

$$\frac{D}{P_1 P_2} = \frac{3 \times 10^{-7}(1-e^{(0.007d)^2})}{d^{0.4}}$$

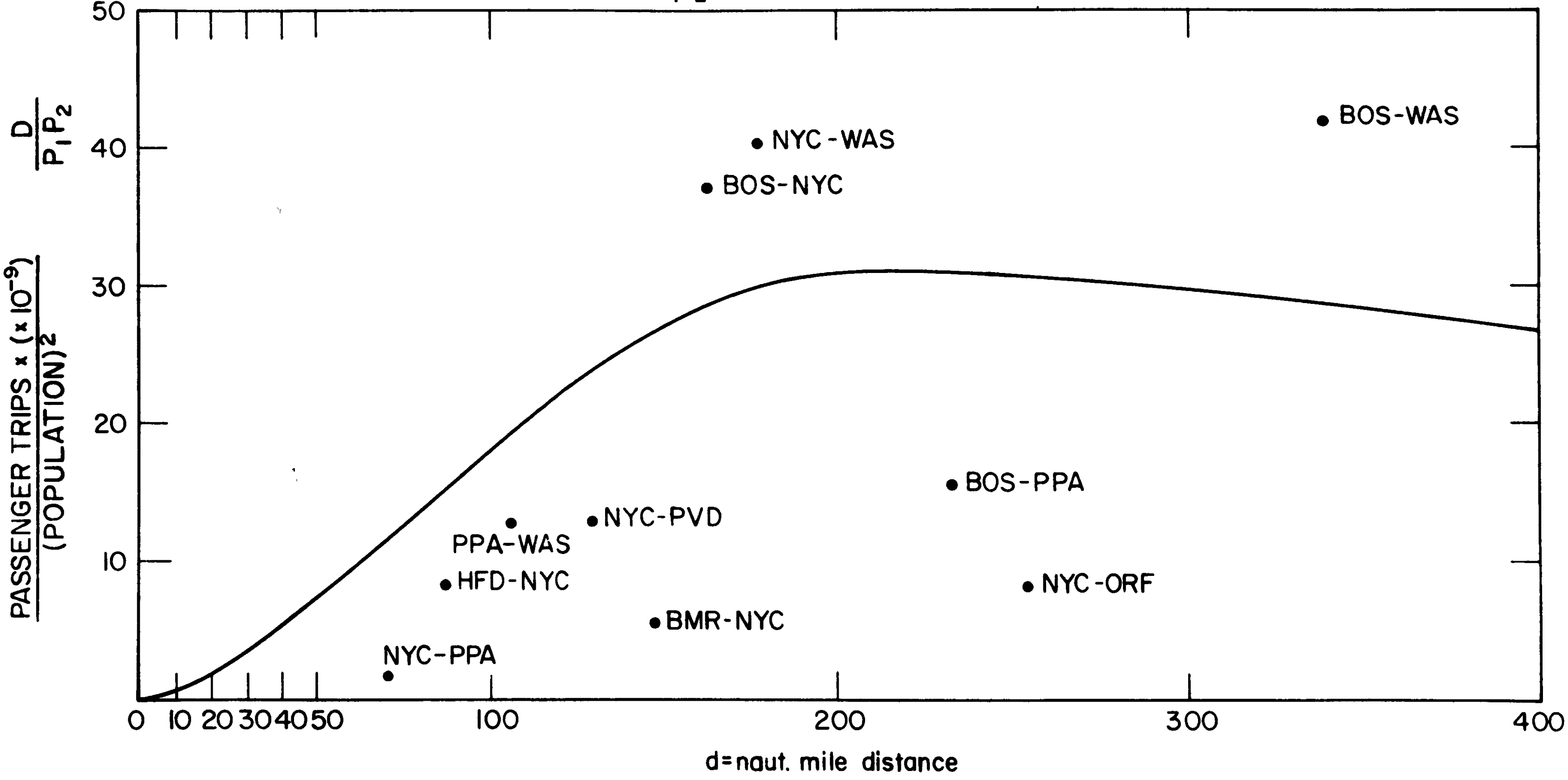


FIG. IV-2

When realistic demand predictions are obtained, they will be used to determine optimum schedules and aircraft sizes, etc.

DETERMINATION OF DIRECT SERVICE ROUTES

The next step was to choose the arcs to be flown, since not all city pairs generate enough demand to warrant direct service. The criteria utilized were two. Service would be given any arc over which demand was greater than 100 passengers per day. Also, service would connect each terminal with the two closest terminals.

With 50 terminals the possible number of direct routes is 2,450. This determination of those routes which would be flown reduced this number to 503. On the remaining 1,900 or so possibilities, it is necessary to follow some indirect routing through the system. On the average, one intermediate stop was necessary for travellers in the system.

To illustrate the effect of passenger flow on the system network, Figure IV-3 shows the weighted distribution of aircraft hops resulting from the network solution. It is pertinent to notice the large number of hops under thirty miles, and that the average hop was 94 miles. This distribution may be compared with Figure IV-4 which shows the unweighted distribution of intercity distances within the corridor.

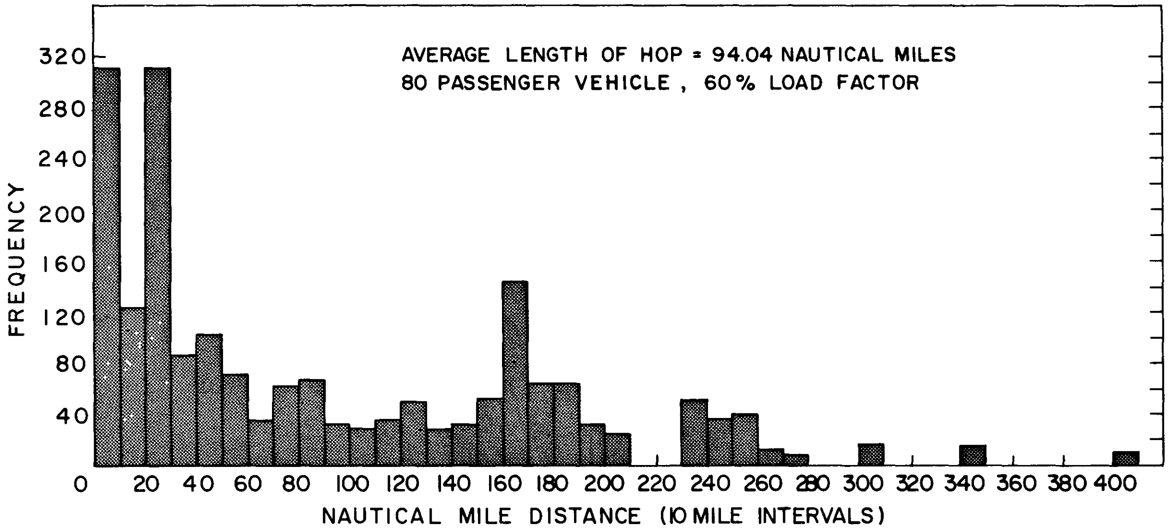


FIG. IV-3 DISTRIBUTION OF NAUTICAL MILE DISTANCES PER HOP (INITIAL DEMAND SOLUTION)

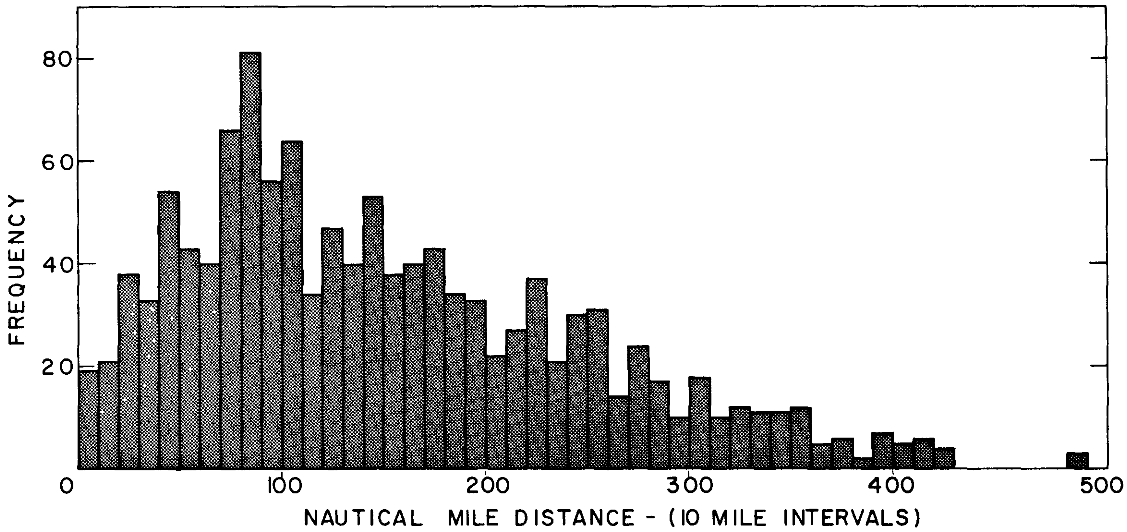


FIG. IV-4 DISTRIBUTION OF NAUTICAL MILE DISTANCES BETWEEN CITY PAIRS - NE CORRIDOR (ALL CITY PAIRS)

PASSENGER FLOW SOLUTION

Given the origin-destination demand data, and the criteria for establishing service arcs, a simple multi-commodity network flow solution was used to determine the daily number of passengers using each service. For example, a passenger from Lawrence, Mass. may travel to Boston, and along either direct or indirect service arcsto his destination, such as to ensure a least distance or least time trip for himself. The total solution minimized total travel distance and gave the total system passenger miles in an average day. Total daily onboard passengers were given for each service, and were used to estimate the number of flight services required for that particular route. The number of passengers using each terminal for starting or ending a trip was also available. When time of day demands are estimated, a similar solution will be obtained to provide schedules such as to minimize total passenger travel time.

It is intended to study the effect of increasing the penetration of the air system into the short range market by varying the constants of the exponential function used to modify the gravity model. To date, only one demand model and solution has been completed. It produced a system total of 3 billion passenger miles per year and handled 16.7 million passengers per year (compared to 35 billion revenue passenger miles and 83 million passengers for all U.S. carriers during 1964).

TABLE IV-2

ONE WAY SERVICES BETWEEN NORTHEAST TERMINALS PER DAY

	DUL	BAL	BOS	BOC	MAN	WOR	NBD	PVD	WIL	PHL	TRE	REA	LAN	ALL	HAR	WBA	SPR	PIT	BDL	JFK	LGA	JRB	EWR	BDR
DCA	1		4							3										8	7	2	1	
DUL										6										4	5			
BAL																				8	4			
BOS				12																13	13	4	17	
BOC						16		7		8										10	10	37	22	
MAN																								
WOR																	28							
NBD																								
PVD										9										18	10		8	
WIL										20											3			
PHL																					7		4	
TRE																						7		
REA													45	57										
LAN															11									
ALL															13								66	
HAR																					14			
WBA																								
SPR																					23			
PIT																								
BDL																								
JFK																					18			
LGA																						54		
JRB																							50	
EWR																								
BDR																								

	HVN	WBY	GON	HFD	ACY	BMR	WAS	MIT	TBO	NYC	ORF	RIC	PPA	PHF	YRK	AVP	SGC	NWK	ISP	EQU	EHM	PWM	FIT	BTN	LAW
DCA							20	5		3		9	13												
DUL							2	4		2			11												
BAL						6	2						8												
BOS							5	5	3	21	3		12												27
BOC						5		4	3	4	2		10										6	2	
MAN																									7
WOR													7												
NBD																								14	
PVD			6			4	4			9			7												
WIL						5																			
PHL				5		4	4	10		16	4	5	21	3			6								
TRE													5												
REA													36												
LAN															16										
ALL																9									
HAR																									
WBA																									
SPR						8							9												
PIT																							5		
BDL				25																					
JFK					6	8	8		20		7	10	7	12											
LGA					16	10	11	33		26	9	6	9	5											
JRB						3	3		2				9												
EWR						5	17			9	5	2	6												
BDR	16												21					8							

	HVN	WBY	GON	HFD	ACY	BMR	WAS	MIT	TBO	NYC	ORF	RIC	PPA	PHF	YRK	AVP	SGC	NWK	ISP	EQU	EHM	PWM	FIT	BTN	LAW
HVN																									
WBY	9																								
GON																									
HFD	15	1																							
ACY																									
BMR				39																					
WAS				44		11																			
MIT						8	8																		
TBO						4	5																		
NYC						10	5		10																
ORF						4	6	8		5															
RIC																									
PPA					4	10	18	10	9	6	11	11													
PHF												5	15												
YRK																									
AVP																									
SGC						8	3	30					5												
NWK	23																36								
ISP								42																	
EQU																			32						
EHM		16																		22					
PWM																									
FIT																									
BTN																									
LAW																					6			

Frequency of Service

By assuming a 60 per cent load factor for an 80-passenger vehicle, it was possible to produce a first estimate of the frequency of flight services between any given pair of service points. The results are given in Table IV-2. The frequency of service for differing load factors and vehicle size can be easily estimated by making frequency inversely proportional to the onboard loads (the product of load factor times capacity). The average onboard load is 48 in the above example.

Service Scheduling

If accurate demand data were available giving time of day passenger flows (as will be the result of a good centralized computer reservation system), it would be possible to establish an optimum schedule, and determine fleet size and optimal system profits. In the absence of such data, it is reasonable to use gross data and methods to indicate fleet size and potential aircraft utilization in the system.

Fleet Productivity

With the passenger demand model indicating 3 billion passenger miles yearly, it is a simple matter to determine fleet size required as a function of average block speed, vehicle utilization, load factor and passenger capacity. Figure IV-5 shows typical results for a utilization of 3,000 hours per year, and an average load factor of 60 per cent. Vehicles from the vehicle design studies are shown.

Vehicle Utilization

If the demand data by time of day were available, the optimum scheduling would give definite values for vehicle utilizations. In their absence we can use gross methods to dispel any prejudice towards the possibility of obtaining high utilizations with short haul vehicles in a busy system. If we define a useful airline day to consist of 18 hours from 6 AM to 12 Midnight, and define:

$T = t_B + t_S$ = total trip time (minutes)

t_B = average block time (minutes)

t_S = average ground stop loading time (transit and turnaround)

and assume progressive maintenance on the fleet is done at night, then the number of trips/day is

$$N = \frac{18 \times 60}{T}$$

The potential utilization, U_p , (hours/day) is given by

$$U_p = N. \frac{t_B}{60} = 18. \left(\frac{t_B}{T}\right) = \frac{18}{1 + t_S/t_B}$$

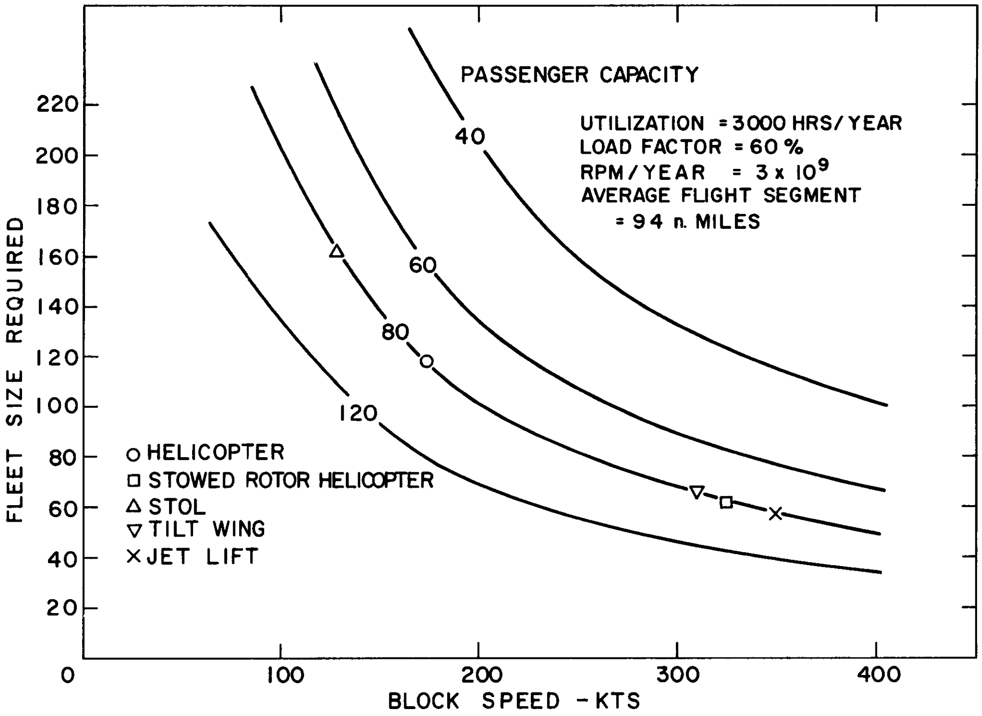


FIG. IV-5 FLEET PRODUCTIVITY TO MATCH TRAFFIC DEMAND

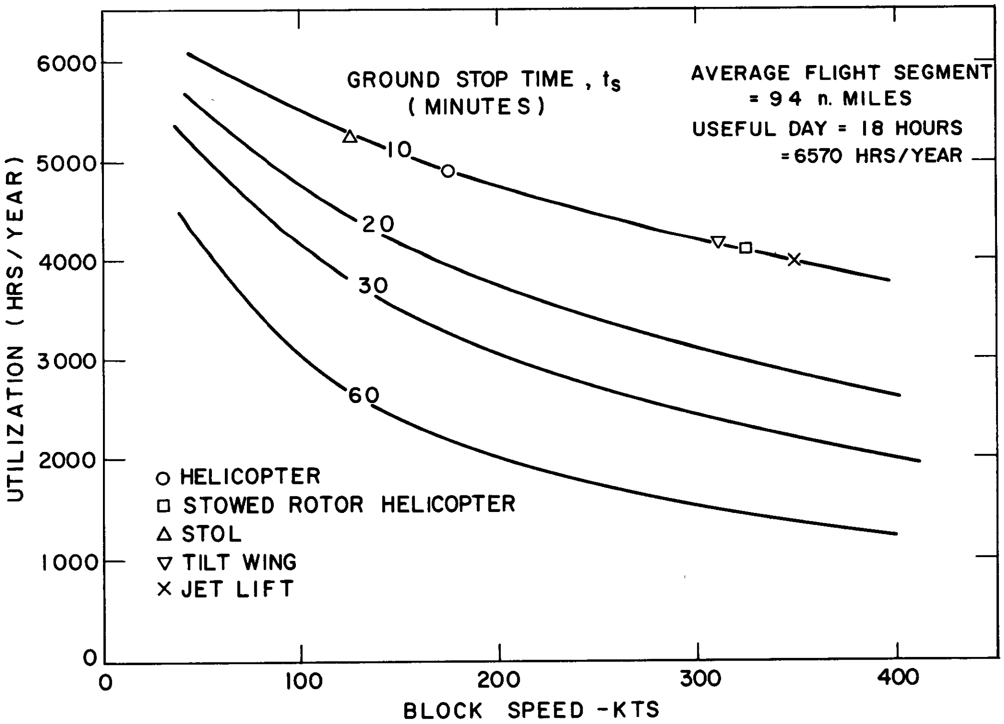


FIG. IV -6 POTENTIAL UTILIZATION VALUES

The potential vehicle utilization is plotted in Figure IV-6 as a function of ground stop time, t_S, and block speed (for an average flight segment of 94 miles) and several typical vehicles from the design studies are shown. The maximum ground stop time necessary for a 100 passenger exchange at one of the major terminals is estimated to be 10 minutes in the section on ground facilities. Average stop times would probably be of the order of 5 minutes, as currently being bettered by the helicopter airlines. The results show that if a short haul vehicle were kept busy, and ground stop times kept small, the potential utilizations can be well over 3,000 hours per year.

This contradicts current experience and thinking about short haul vehicles, especially in airline circles. The reasons for lower utilizations are explained by lack of traffic to keep the vehicles busy. Discussions with the helicopter carriers has indicated that they could increase vehicle utilizations at the expense of load factor. Their small fleet sizes also necessitate the availability of spare aircraft for backup in the event of maintenance and flight training. This has usually meant that the scheduled services could be performed with a small fraction of the total fleet, and, therefore, low fleet utilizations. A larger fleet and schedule would eliminate this effect, and the domestic trunks have only a few per cent of their fleets as cover, training, or maintenance aircraft.

The point to be made is that short haul transport systems fortunate enough to have large networks do not necessarily have low vehicle utilizations. A secondary point indicated by Figure IV-6 is that as block speed is increased for a given stop time, t_S, the potential utilization decreases due to less time being spent airborne.

CONCLUSIONS

While the passenger demand for a 1980 VTOL Airbus system in the Northeast Corridor is not known, it was found necessary to hypothesize some demand distribution to give an idea of the size of the system, the number of vehicles required, the distribution and average length of aircraft hops, and the size of passenger loads or demands upon the various routes of the system. Since both direct and indirect costs are dependent upon size, better demand data is required to allow optimization methods to determine vehicle size, and the size and distribution of ground facilities.

Given good demand data, it is clear that an air transport system possesses unique capabilities compared to any ground system. Complete area coverage can be provided within the Northeast Corridor and with the addition of any new terminal to the system, direct service becomes feasible to all other terminals within the system. With adequate knowledge of passenger travel, computer based optimization methods exist to optimize the system services. With the variables of frequency of service, vehicle capacity and speed, the air system can respond in a flexible efficient manner to traffic variations in daily, seasonal, and long term cycles. With the small VTOL terminal, it is a simple matter to initiate or discontinue service at any new point in the corridor.

The fleet productivity with large capacity, high speed vehicles is potentially so great that the number of vehicles required within the corridor area would be of the order of 100. Since this would be considered a small production run by present aircraft manufacturers, the V/STOL vehicles offered by 1980 would be designed for a much broader market. This market exists in other areas of the U.S.A., and in Europe. The probable purchasers of these vehicles would be present airline systems who are already looking for efficient V/STOL vehicles to replace piston and jet equipment on their systems, and perhaps looking to provide feeder services to their longer range jet services. While the network has been considered as a single entity, it infringes upon the present traffic rights of a number of domestic and local airlines.

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PART V.

GROUND FACILITIES

V

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Tables

INTRODUCTION

There are three classes of stations considered necessary for the V/STOL Airbus System: Major City Center Terminals, Airbus Stops, and Major Airport Terminals.

Major city center sites would probably be necessary at Boston, New York (at Wall Street and in the vicinity of the Pan Am building), Philadelphia, Baltimore and Washington, D.C. In such terminals, it is expected that maximum traffic volumes might be as high as 10,000 passengers per day.

For smaller cities, Airbus stopping points would be placed at the city center, or the local airport if travel times and convenience are good. Such cities would range from Norfolk Airport at 1,400 passengers per day, to Fitchburg, Mass. at 80 passengers per day. A listing of sites taken for these cities is given in Part IV, System Network Studies.

Major airport passenger terminals would exist at all major airports, either as a separate building or as a part of the available terminal buildings. At five airports, maintenance facilities and hangar storage are provided. These have been taken as Boston, Kennedy and Newark, Dulles and Philadelphia.

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 cloverleafs, 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.

It is clear that a smaller area site will be easier to locate in the city. One particularly attractive idea is to construct unified transportation terminals in the city center so that rail, taxi, bus, subway, auto and air all use the same building.

For the VTOL system, one envisages a parking garage with a subway or rail station in the basement levels, a bus terminal and taxi stop on street levels, a number of floors for auto parking and a VTOL air service off a roof top terminal. Elevators connecting all floors is yet another transportation link in such a terminal. Similarly, present railroad yards in downtown areas may be covered by elevated structure to permit air operations, and re-vitalize the rail passenger buildings in present downtown areas.

Although the elevated air terminal has problems from low weather ceilings and uncertain winds, this report has considered roof top operations from the terminal buildings as being the probable form of a city center terminal. At minor stations, ground level operations have been used because of the smaller investments required. Accordingly, the design of a maximum volume, city center terminal equipped with all mechanical facilities to handle large crowds, and a minimal cost ground stop facility have been investigated; the former to show the maximum costs in a full size terminal and the possibility of handling large passenger loads at short stopping times, and the latter to show that a minimal facility can be installed at remote sites at very little cost to initiate service in the system. Of course, every terminal in the V/STOL system will be different in size and shape, depending on its passenger volumes, but the description of these two terminals encompasses the range of terminal buildings required.

ALTERNATIVE DESIGNS FOR A MAJOR CITY CENTER V/STOL TERMINAL

Before investigating alternative designs, it is appropriate at this point to explain the choice of unit structural and land prices.

Unit Structural Prices

In determining the unit costs of concrete construction, reference was made to concrete highway bridge superstructure costs (see Ref. V-1).

Actual state prices for bridge superstructure unit costs (70-foot spans) were given for New York ($9.47 per square foot), Connecticut-Rhode Island ($9.30), Massachusetts ($8.92), New Jersey ($10.80) and Maryland ($8.80).

The average came to $9.46 per square foot and the figure of $10.00 per square foot was taken as being a representative round number. Discussions with the Department of Civil Engineering, M.I.T. indicated that this would probably be a conservative figure for the elevated structures in this section.

Unit Land Prices

Within a given central business district, the land costs vary considerably, depending upon the precise location. The following averages for the five main population centers were obtained. (See Ref. V-5.)

LOCATION	COST OF LAND($/Sq.Ft.)
Boston	15.00
New York City	45.00
Philadelphia	20.00
Baltimore	15.00
Washington, D.C.	20.00

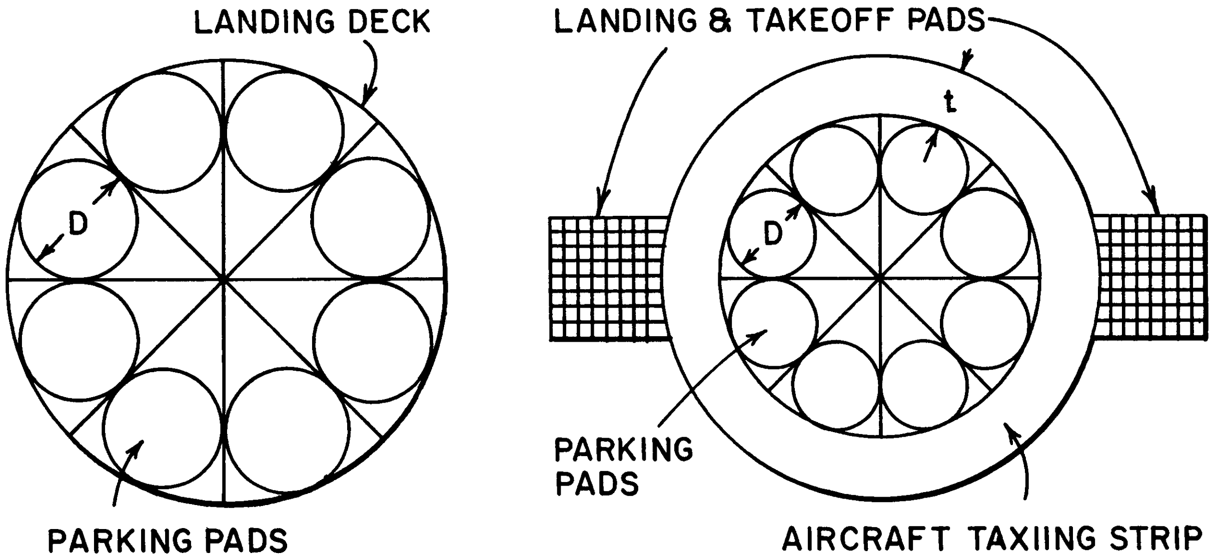
The overall average is $23.00 per square foot and this figure will be taken as the unit cost of downtown land.

Alternative designs for major V/STOL terminals will now be considered. In particular, structural and land costs for various alternatives will be explored at this point. In all cases, it is assumed that terminal building furnishing costs are a function of passenger traffic volumes.

Elevated VTOL Terminals

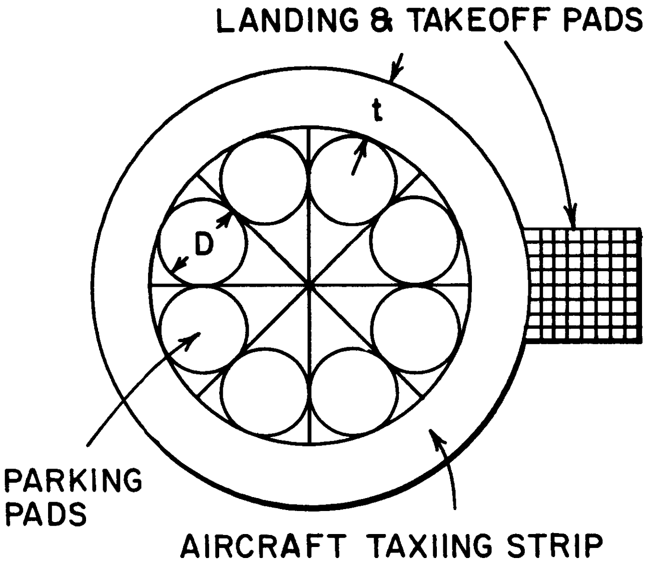
The following configurations, A1, A2, A3, B1, B2, B3, B4, C1, C2, C3 and C4, shown in Figure V-1, represent various alternative plans. In each case (except A1), the aircraft is meant to take off from and land on special pads set aside from the parking area. In the case of A1, the aircraft is meant to take off from and land on the respective parking pad. The pads may be steel grill structures to keep head and downwash off the working surface, and perhaps provide sound suppression.

Each of the following alternatives consists of an elevated landing deck over a passenger terminal. As the costs of each type are largely functions of plan area, these have been calculated in terms of D, the parking pad diameter.



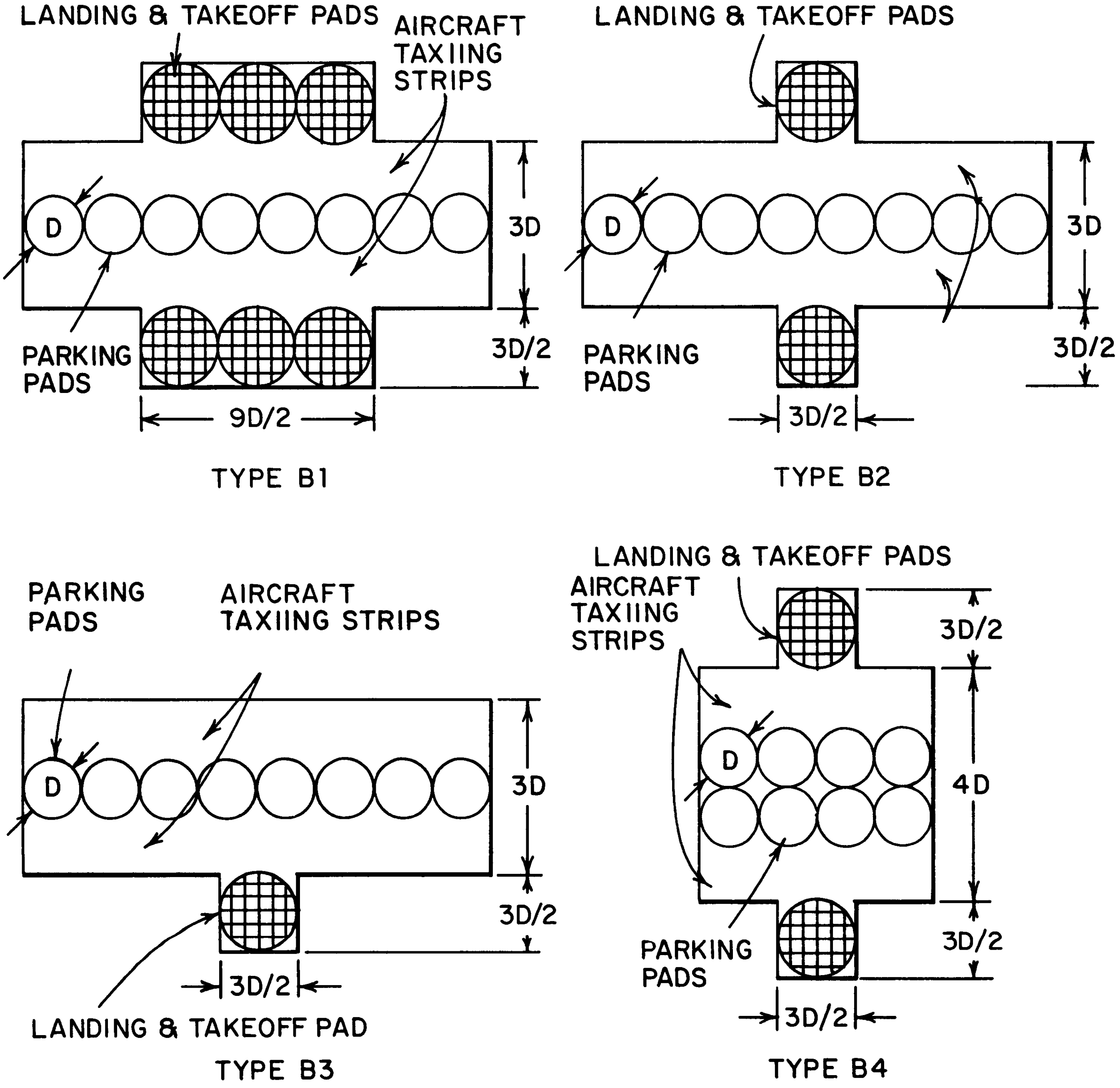
TYPE A1

TYPE A2



TYPE A3

FIG. V-1A CIRCULAR VTOL TERMINAL CONFIGURATIONS - A SERIES



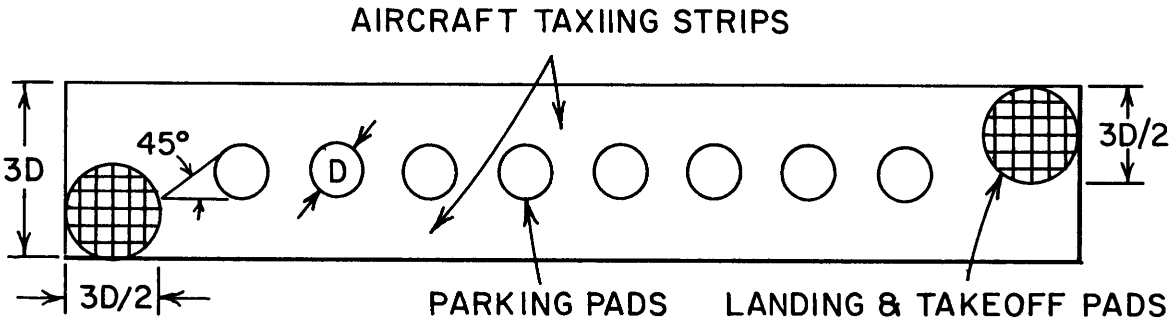
TYPE B1

TYPE B2

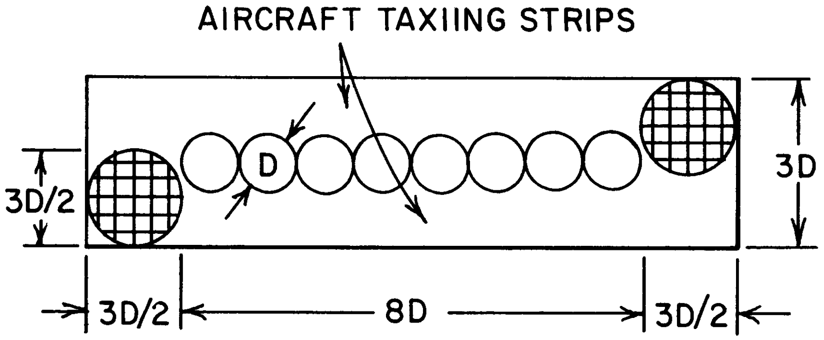
TYPE B3

TYPE B4

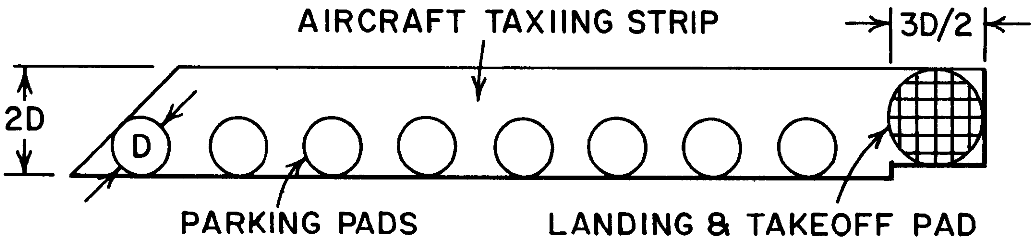
FIG. V-1B LONG VTOL CONFIGURATIONS - B SERIES



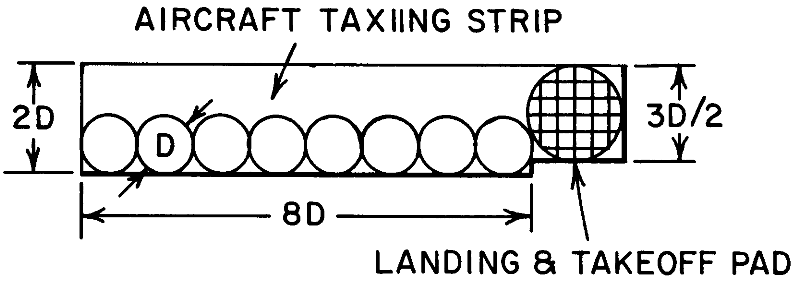
TYPE C1



TYPE C2



TYPE C3



TYPE C4

FIG. V-1C LONG VTOL CONFIGURATIONS - C SERIES

ALTERNATIVE	PLAN AREA (Square Feet)
A1	$10.25\ D^2$
A2	$14.75\ D^2 + 1135.08D + 31415.60$
A3	$12.50\ D^2 + 851,32D + 17671.50$
B1	$37.50\ D^2$
B2	$38.50\ D^2$
B3	$18.25\ D^2$
B4	$20.50\ D^2$
C1	$49.94\ D^2$
C2	$33.00\ D^2$
C3	$24.88\ D^2$
C4	$18.25\ D^2$

As the structural and land costs have been assumed to be directly proportional to the plan area, alternatives A1, B3 and C4 appear most promising and will be investigated further. However, the major emphasis will be placed on A1.

Structural costs for various parking pad diameters have been calculated by multiplying the appropriate plan areas by the unit cost of construction. See Figure V-3.

In the case of land costs, a similar procedure was followed except that the areas used were slightly larger than the plan areas. This was to provide suitable space for parking, etc.

The following table gives land areas for A1, B3 and C4. D is the parking pad diameter. See Figure V-3 for land costs associated with these terminals.

ALTERNATIVE	LAND AREAS
A1	13.054 D^2
B3	28.000 D^2
C4	19.000 D^2

Elevated STOL Terminals

In addition to the normal buildings associated with a VTOL port, the STOL facility will require at least two short runways, in order to provide wind coverage for a system reliability goal of 99.5%. In closely settled urban areas, the acquisition of sufficient suitable land is expected to be a problem. In view of this, it is felt that an elevated structure over some existing right of way, such as a highway, railroad track or river would be appropriate. As in the case of the alternative VTOL facility configurations, structural costs are largely functions of plan areas.

In the following diagram (Figure V-2)

L = Runway length
D = Parking pad diameter
W = Runway width
w = Taxiway width
S = Runway/Taxiway centerline separation

STOL TERMINAL LAYOUT

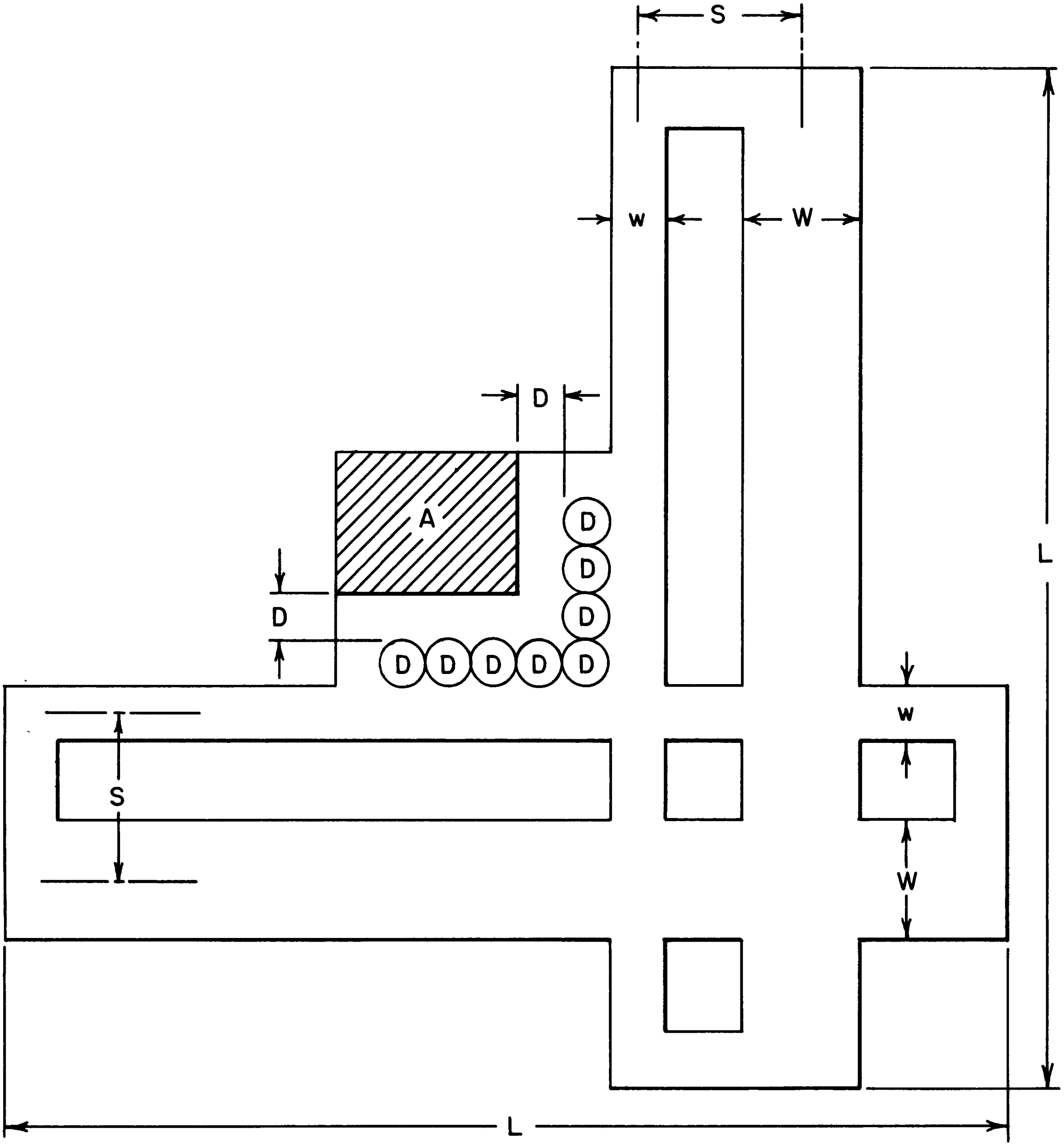


FIG. V-2

For STOL cases, the following values were assumed:

$W = 150'$

$w = 75'$

$S = 400'$ (Ref. V-2.)

$L = 1500', 1000', 750'$ (3 cases)

As was the case for VTOL, structural and land costs for various parking pad diameters were calculated by multiplying the appropriate plan areas by the unit costs. The following are the plan and land areas for the various elevated STOL cases:

$$\text{PLAN AREA} = 450L + 18D^2 + 35{,}625$$

$$\text{LAND AREA} = 1025L + 18D^2 - 262{,}656$$

The difference in area arises from the fact that the land area includes the space between runways and taxiways, whereas the plan area does not. Figure V-4 gives the structural and land costs for the elevated STOL facility.

Ground Level STOL Terminals

The ground level STOL differs from the elevated version in two major respects, viz.

a) The cost of runway and ramp construction at ground level will be $10.00 per square yard of plan area. The plan area will be the same as for the elevated STOL.

VTOL
TERMINAL INVESTMENT COSTS

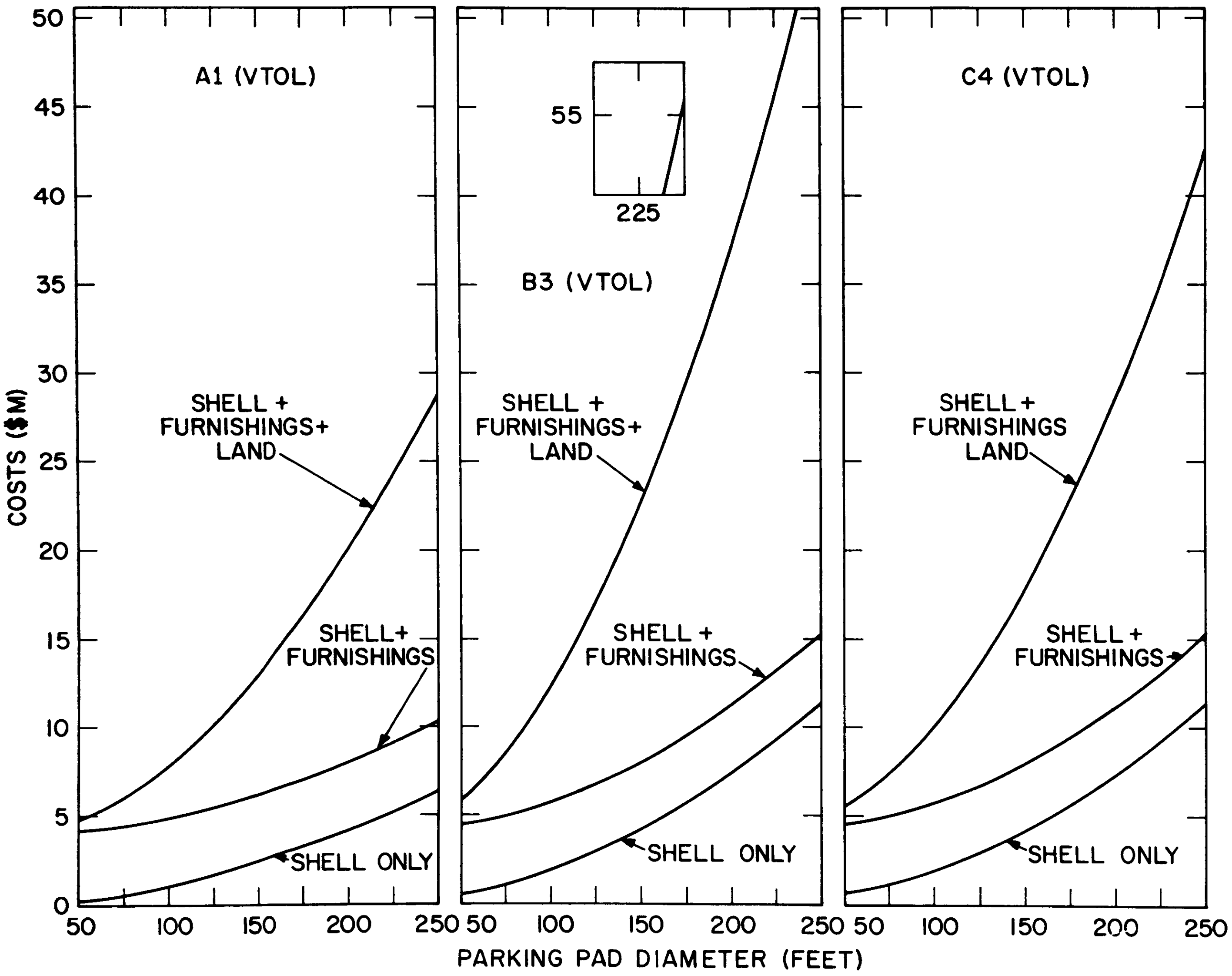


FIG. V - 3

ELEVATED STOL
TERMINAL INVESTMENT COSTS

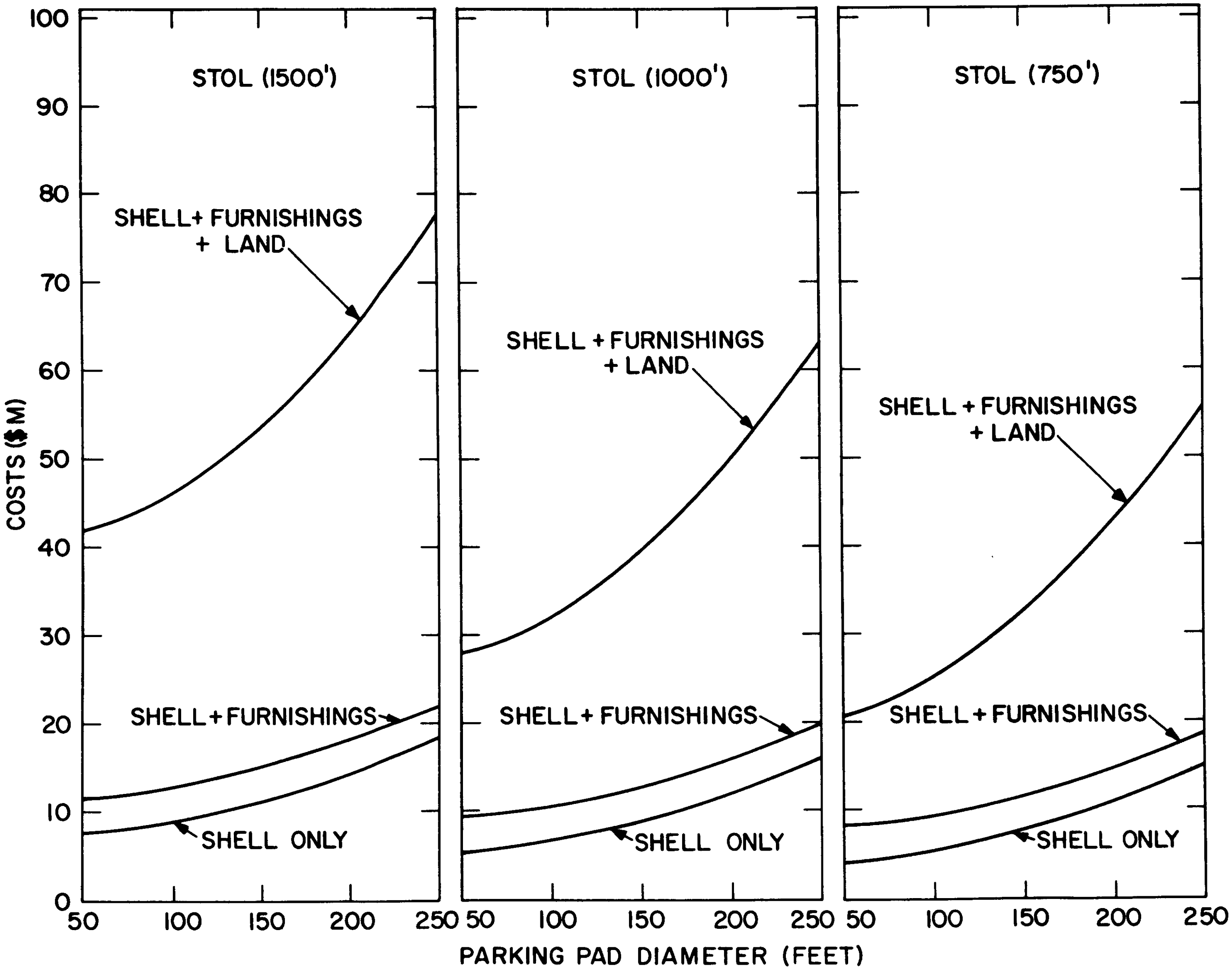


FIG. V-4

GROUND LEVEL STOL
TERMINAL INVESTMENT COSTS

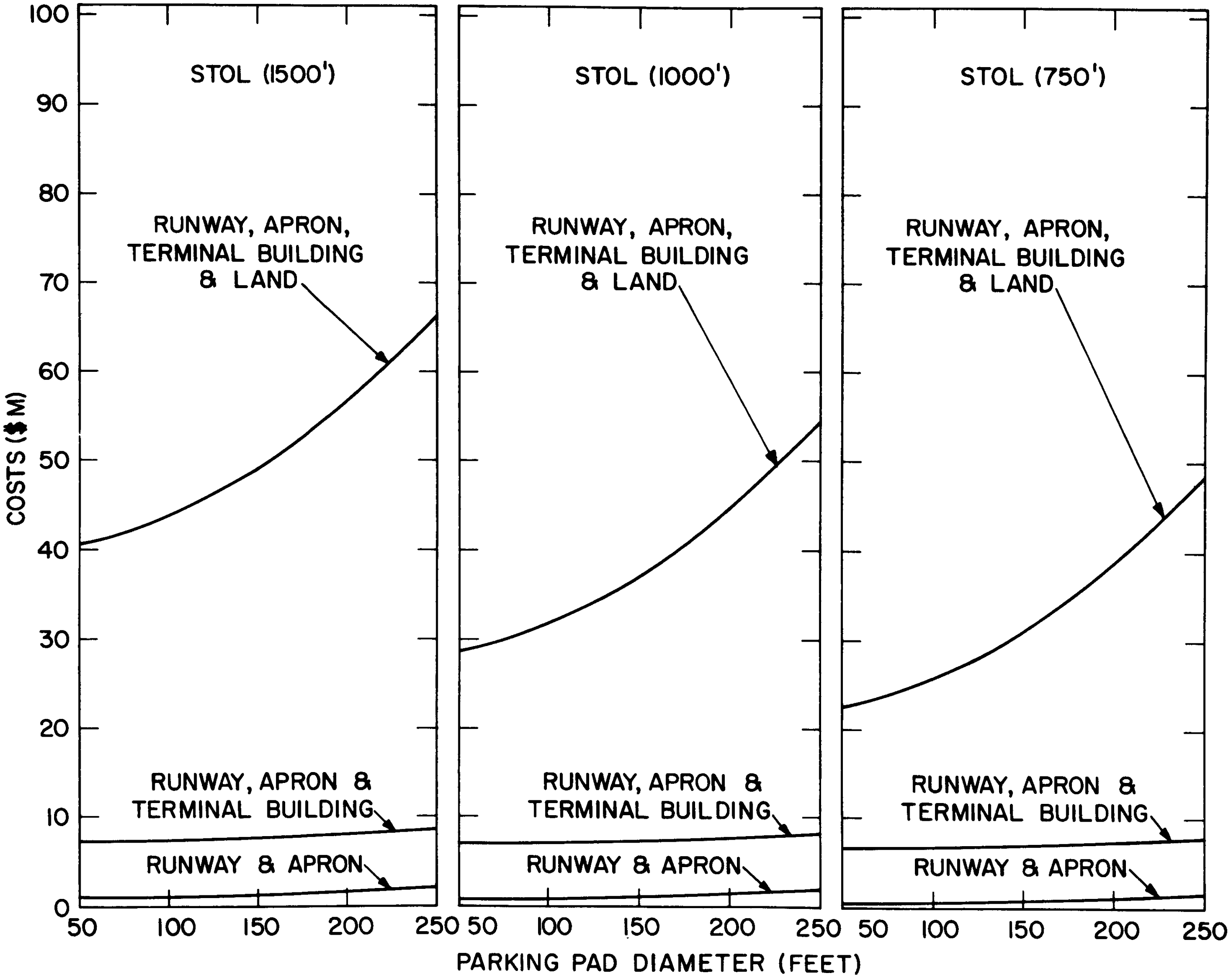


FIG. V - 5

b) An additional area, A (see Figure V-2) would be required for the terminal building, which would now be adjacent to the apron area and not under it, as was the case with the elevated structure. The area A is taken as equivalent to the area of the terminal type A1 and would be 135,000 square feet. The land cost would rise by $3.105 million to cover the additional area.

c) The cost of constructing a terminal building on the area A has been omitted. It would probably add 2-3 million dollars to the ground level STOL terminal construction costs.

Figure V-5 gives the structural and land costs for the ground level STOL facility.

DESCRIPTION OF A VTOL PASSENGER TERMINAL

In order to provide a basis for estimating the total operating costs of the Airbus System terminals, a concept of a possible circular VTOL port, to be called type A1, has been sketched in Figure V-6.

The terminal consists of a circular prestressed concrete structure, on top of which eight landing pads are located about a common center. All passenger handling is done at the first floor level, the second floor being devoted entirely to the landing deck.

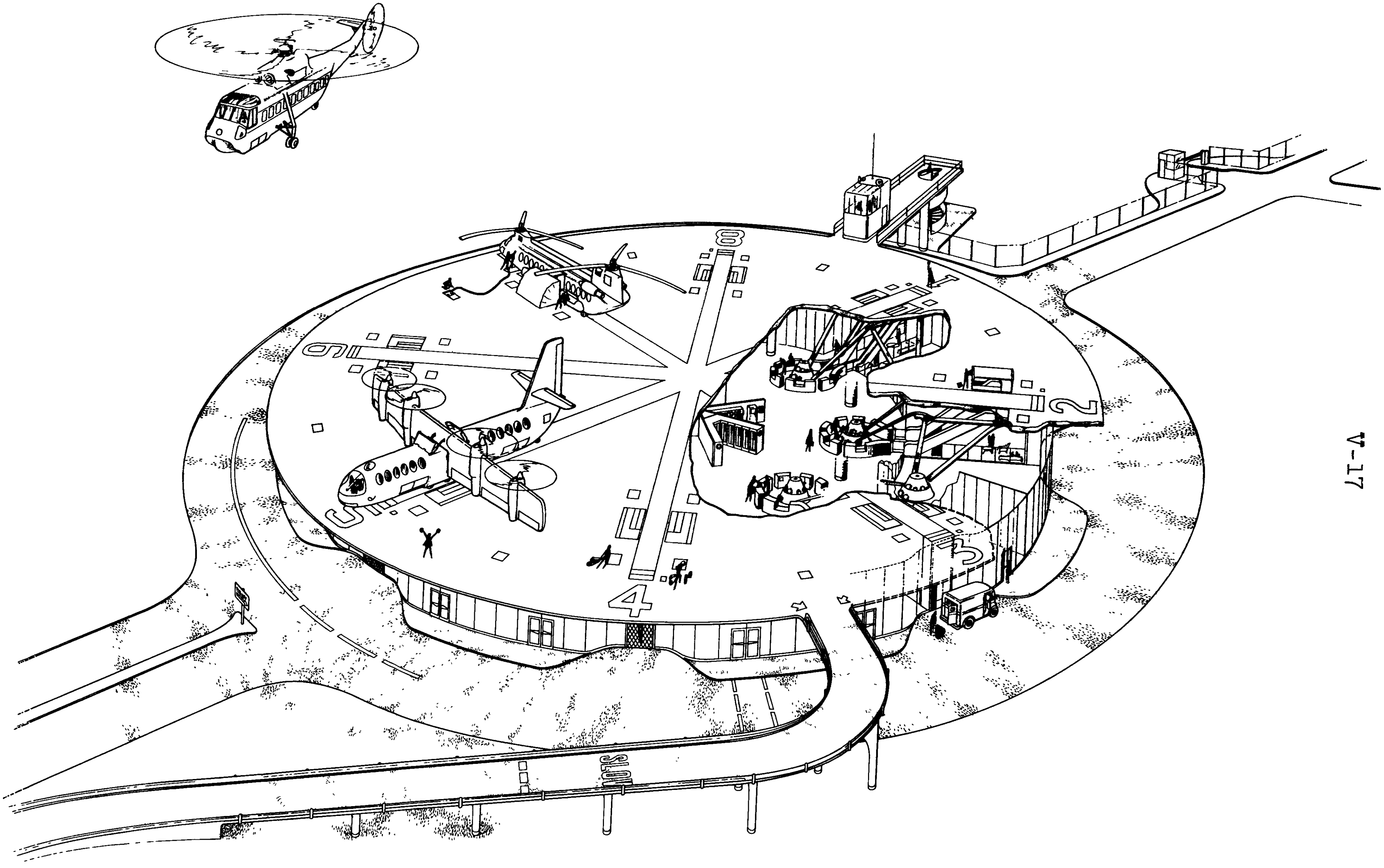


FIGURE V-6 MAJOR CITY CENTER TERMINAL

An access road, designed to carry one way ground traffic surrounds the entire building, while on one side, there is an access ramp leading to the deck. The latter ramp is for the use of emergency vehicles only.

Passenger Handling

The procedure followed by a typical departing passenger would be as follows:

The passenger would arrive by some road vehicle and be deposited on the sidewalk surrounding the building.

From here, he would enter one of the many doors set in the glass walls and from computer driven information boards, determine the location of the check-in counter appropriate to his flight. The gate would open after load control had been transferred from the vehicle's last station, roughly 20 minutes before departure.

At the check-in counter, any baggage would be weighed, labeled and placed on a continuously rotating carousel behind the counter. The carousel would serve as both a loading and storage device.

From the sides of the carousel, conveyor belts extend up to a height level with the baggage loading doors of the vehicle. Baggage would be stored on two shelves in the carousel. During the initial stages of loading, the carousel would be revolved and baggage from the lower shelf would be taken up and loaded through the front loading door. In the latter stages of loading, the shelf in the carousel would be lowered and the remaining baggage would be sent to the rear loading door. This procedure would enable the clerks to assist in the pre-sorting of the baggage and so save time later.

Meanwhile, the passenger would have proceeded to a special boarding area behind the loading carousel. From this area(to which entry would be restricted to ticket holders),the two passenger loading escalators lead directly into the aircraft to ensure rapid transfer of passengers during the loading period. Because of the short stopping times, it is expected that most passengers will be waiting for the vehicle's arrival. Check-in will stop 5 minutes before departure time.

The procedure would be reversed for the disembarking passenger:

The passengers would descend from the vehicle using the two escalators.

The baggage would be sent down another set of conveyor belts to a "collection" carousel located on the first floor between the ticket counters. The passengers would claim their baggage from this carousel on a self-service basis, on their way out to the sidewalk.

Vehicle Handling

The landing deck has been kept clear of any obstructions. No structures and no ground servicing carts or vehicles are on the deck. The only people on the deck are the ramp servicing personnel, who will wear helmets with two-way radio for communication with pilots and the deck controller in the cab. Passengers will disembark under a cover which rises from the deck after the aircraft has arrived. This has the twofold purpose of preventing passengers from getting onto the roof, and protecting them from rain and downwash, jet blast, etc.

After the vehicle has touched down, the ramp personnel will move in to raise the passenger cover and open the door, to plug in electrical and airconditioning supplies (if necessary) and to begin rapid refueling from installed hydrants, flush in the pad. They will then move to baggage handling, opening the baggage bins on the aircraft, and unloading bags onto the conveyor belts which lead to the discharge carousels.

When the bags and passengers have unloaded, the escalators and conveyor belts will start bringing the departing passengers and bags, and the ramp attendants will change over to loading bags.

The terminal also has an arrangement for handling mail and express of the Post Office or Railway Express Agency. Elevators are placed adjacent to the sidewalk under each aircraft parking area. Mail or express trucks arrive, deliver into one elevator and pickup from another, using a key. The ramp attendants draw the elevators up to the deck, and load and unload directly into them.

When the aircraft is ready to depart, the ramp attendant will signal for pilot for starting, and the deck controller will clear the departure for takeoff.

Vehicle Turn Around Time

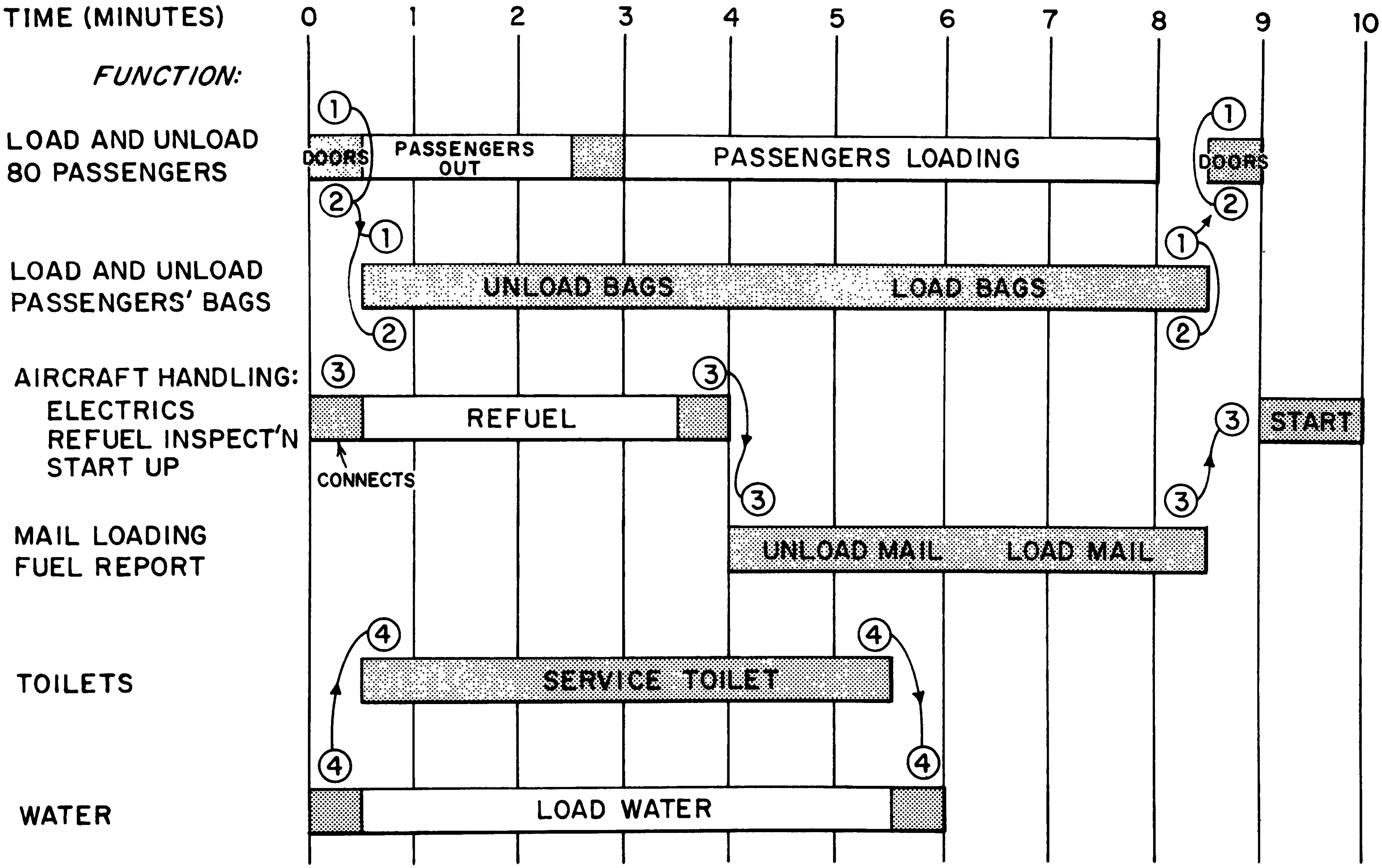
The above process is expected to be accomplished in less than 10 minutes during busy periods. A time and motion study (similar to those which the airlines use to show how their airplanes may be turned around in 30 minutes) has been carried out to see if there is any physical reason preventing such short stop times.

Time to Unload 80 Passengers

Allow 30 seconds after touchdown to open doors, raise the passenger cover, and start the passenger escalators. Meanwhile passengers can unbuckle seat belts and begin to put on coats, enter the aisle, etc. If we use a passenger flow down the aircraft aisle of one every two seconds (based on small sample observations), and two unloading flows, we can unload 80 passengers in roughly 90 seconds. The capacity of the escalators is estimated at one passenger per second and there are two escalators, so that the flow restriction occurs in the aisle of the aircraft. About 30 seconds is required to allow the last passenger to reach ground level before reversing the escalators. Therefore, the total passenger process takes 150 seconds or 2.5 minutes.

Time to Load 80 Passengers

The loading time usually takes longer due to the passengers finding their seats in a random manner and blocking the aisle while taking off coats, etc. The unloading time has been doubled to allow 5 minutes for this factor, and airline studies agree with this estimate. No straggling check-in passenger has been allowed.



* WORKING POSITION OF RAMP ATTENDANTS, ①,②,③,④.

FIG. V-7 WORK LOADING DURING A FULL LOADING PROCESS.

Baggage Loading and Unloading

With two baggage attendants, and two conveyor belts, the critical factor seems to be how fast the attendants will work. If they will work at the rate of one article every six seconds, the load and unload time for 160 bags would both be 8 minutes.

Time to Refuel Aircraft

The hydrants have a refueling rate of 300 gallons/minute, and the average fuel load is estimated at 750 gallons for the Airbus network. The fuel flow time is 2.5 minutes, and if one minute is allowed for connection and disconnection of the hose and fuel tank, the total refueling can be accomplished in 3.5 minutes.

Toilet Servicing Time

This will not occur at every stop. Allow five minutes for this task.

Water Supply Time

Similarly, the water supply will probably not be replenished at every stop. With water hydrants on the roof, this can be accomplished in three minutes including connection and disconnection times.

From Figure V-7, it is seen that a maximum of four ramp attendents could perform all the necessary services to turn the Airbus vehicle around in 10 minutes for a full 80 passengers off and on. The average on board load expected is 48 passengers, and the average pickup load 24 passengers. Thus, the average turn around can be performed in less than 10 minutes, or alternatively, fewer ramp attendants would be required. A minimum of ramp attendants would be two; one to refuel, etc.; and the second to open the passenger door and unload baggage.

COST OF TERMINAL BUILDING FURNISHINGS

For the purposes of this report, furnishings have been used in a broad sense to cover items not directly associated with the actual shell of the building.

It has been assumed that the furnishings would be largely independent of terminal type and more a function of traffic volumes. Accordingly, terminal type A1 will be examined to determine the furnishing costs.

According to F.A.A. design recommendations, a total floor space area of 135,000 square feet is appropriate for a daily volume of 10,000 passengers. Such an area could be obtained from a circle of diameter 415 feet.

Although the diameter of the landing deck is 540 feet for a pad diameter of 150 feet, the diameter of the terminal itself is only 415 feet. Thus there is an overhang of some 62 feet around the building. The overhang would be sufficient to cover the surrounding roadway.

In the following determination of furnishing costs, item unit costs were obtained by quotations from the manufacturers concerned.

<u>Concrete Floor</u>	
Diameter = 415 feet	
Area = 135,000 square feet	
Unit Cost = \$10.00 per square yard	
Cost of floor = 10 x $\frac{135,000}{9}$ =	\$ 150,000
<u>Terazzo</u>	
Unit Cost = \$1.30 per sq. ft. (includes labor and materials)	
Area = 135,000 sq. feet.	
Cost = 1.30 x 135,000 =	175,500
<u>Glass Walls</u>	
Allow a rise of 20 feet	
Area = 20 π D where D = 415 feet	
= 20 x 1304 = 26,080 sq. ft.	
Unit Cost = \$3.00 per sq. ft. (includes labor, material and frames)	
Cost of glass = 3 x 26,080 =	78,240

Passenger Escalators

For a rise of 20 feet, unit cost = $40,000

Number required = 16

Cost of escalators = 16 x 40,000 = $640,000

Baggage Belts (from Check-in)

The approximate cost of this item is 25% of the cost of the passenger escalator.

Assume a unit cost = $10,000

Number required = 16

Cost of baggage belts = 16 x 10,000 = 160,000

Baggage Belts (to Carousels)

Assume a cost of $5,000 each

Number required = 32

Cost of baggage belts = 32 x 5,000 = 160,000

Carousels

Unit Cost = $25,000

Number required = 16

Cost of Carousels = 16 x 25,000 = 400,000

Mail Elevators (Hydraulic)

Unit Cost = $20,000

Number required = 8 (one per gate)

Cost of mail elevators = 8 x 20,000 = 160,000

Ticket Counters

Unit Cost = $30.00 per lineal foot

Length required = 450 feet

Cost of counters = 30 x 450 = $ 13,500

Baggage Weighing Scales

Unit Cost = $500

Number required = 32

Cost of scales = 32 x 500 = 16,000

Instrumentation

Cost of full scale control tower (F.A.A.) = $275,000. Since a full scale tower would not be necessary for this size of airport, a figure of $100,000 will be adopted.

Cost of Instrument Landing System = 150,000

Allow $100,000 for communications equipment. This figure includes the associated installation and engineering costs

Cost of communications equipment, etc. = 100,000

Fueling

The cost of a hydrant fueling system suitable for eight gate positions = 372,000

Air Conditioning & Heating

Area = 135,000 sq. ft.

Ceiling height = 20 ft.

Volume = 2,700,00 cu. ft.

For this volume, 600 tons of equipment would be needed.

Unit Cost = $1,000 per ton

Cost of Air Conditioning and Heating plant =	$ 600,000

Ventilation

Unit Cost = 8¢ per cu. ft.

Cost of Ventilation plant =	216,000

Power

Cost of installing power facilities	200,000

Lighting

An acceptable level of lighting intensity is 50-60 foot candles.

Unit Cost for this intensity = $1.50 per sq. ft.

Cost of lighting = 1.50 x 135,000 =	202,500

Plumbing, Drainage & Service (Ref. V-3)

Cost	115,000
TOTAL FURNISHING COST =	$3,908,740

This total furnishings cost is an underestimate but it is believed that the major items have been covered. The actual furnishings cost depends upon contractual arrangements, local labor rates, etc. and the above figures are representative of work performed in the Boston area.

COMPARISON OF VTOL AND STOL TERMINAL COSTS

Structural and Land Costs

It is instructive to compare just the structural and land acquisition costs for the VTOL and STOL city center terminals. Taking a parking pad diameter of 150 feet, the terminal designs are ranked as to total structural plus land, and just land costs in Table V-1.

TABLE V-1 Comparison of VTOL and STOL Terminal Costs

Structural plus Land Costs ($M)		Land Costs ($M)	
VTOL A1	9.1	VTOL A1	6.8
VTOL C4	13.9	VTOL C4	9.8
VTOL B3	18.5	VTOL B3	14.4
GL STOL 100'	34.0	E. STOL 1000'	26.8
E. STOL 1000'	35.7	GL. STOL 1000'	29.9
GL STOL 1500'	42.0	E. STOL 1500'	38.6
E. STOL 1500'	49.8	GL STOL 1500'	41.7

In general, Table V-1 shows that the STOL costs are at least twice that of the VTOL terminals, and that this is mainly due to the very much larger land area required. For example, the ground level, 1000 foot runway, STOL construction and land costs are 34 million dollars compared to VTOL A1 costs of 9.1 million dollars. For commercial STOL transport operations, it is unlikely that less than two runways of 1000 feet in length could be safely used. The land costs or air rights costs associated with purchasing such an area near the city center almost preclude using STOL vehicles. Part VII, on the indirect operating costs of the Airbus System, indicates that in short haul transportation. the terminal facilities costs are dominant.

Total Major Terminal Costs

By adding the furnishings cost, the total terminal cost for VTOL and STOL terminals is obtained. The results are shown in Figures V-3, V-4, and V-5. For a 150 foot parking pad diameter the relative terminal costs are given by Table V-2.

TABLE V-2 Total Terminal Costs

Terminal Type	Total Cost ($M)
VTOL A1	13.1
VTOL C4	17.9
VTOL B3	22.5
GL STOL 1000'	38.0
E. STOL 1000'	39.7
GL STOL 1500'	46.0
E. STOL 1500'	53.8

Comparing VTOL A1 costs with Ground Level, 1000 foot STOL costs shows a factor of almost 3 in major terminal costs.

DESIGN FOR A SMALL AIRBUS TERMINAL

While there is a need for major terminals in the Corridor system, it is envisaged that the majority of the stopping points will be very small, "bus stop" type terminals. At these points, the vehicles will not stop engines or refuel, but will simply discharge and pickup passengers. It is desirable that there be a minimum of investment in facilities such that low traffic levels can be economically served, and also to keep total system investment in ground facilities small. While the previous sections have examined a maximum terminal cost, this section is examining the minimum possible investment in ground facilities.

Ground Level VTOL Airbus Stops

The experience of Los Angeles Airways and San Francisco Oakland Helicopters in constructing helistops for their suburban services may be cited to determine minimal costs for this type of ground facility. Reference V-4 contains full costs associated with establishing a terminal of the type shown in Figure V-8. The stops consist of a simple building to protect waiting passengers, and house a single traffic agent with telephone, toilets and heating (for Northeast Corridor weather). A simple 200 x 200 foot landing pad is used to discharge passengers directly in front of the building, and a baggage cart is used by the traffic agent and the cabin attendant. A substantial parking lot can be

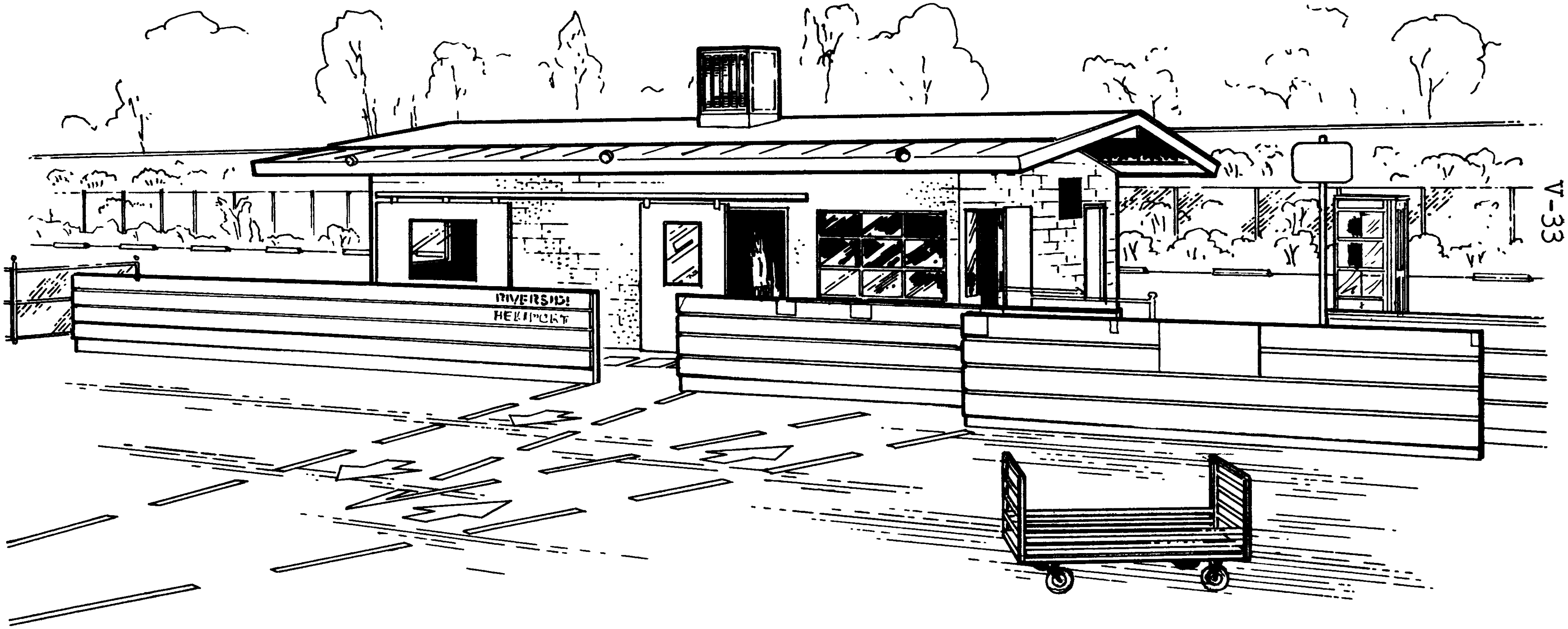


Figure V-8. SMALL AIRBUS TERMINAL

considered, with people waiting in their cars for the arrival just outside the fence which surrounds the pad. This size of terminal is capable of handling up to 1,000 passengers per day, and pickup loads of the order of 50 passengers.

The costs quoted here are representative values taken from Reference V-4.

Cost of Parking Lot Access Road, etc.

The cost varies with size of parking lot, etc. but a minimal cost would be $10,000.

Cost of Terminal Building

The experience of Los Angeles Airways indicates that buildings similar to that shown in Figure V-8 can be constructed and furnished for less than $30,000. For a minimal building, an estimate of $20,000 is taken.

Cost of Landing Pad

The cost of providing a concrete pad surrounded by asphalt with a blast fence, and sufficient lighting for night operations would be of the order of $12,000.

Cost of Communications, and Instrument Landing Facilities

To provide all weather service, sufficient radio navigation and communication equipment must be available to ensure safety for blind approaches. A similar level of cost to the major terminals is incurred, namely $250,000.

Land Costs

Although the experience of Los Angeles Airways indicates that in suburban areas, the local municipalities are willing to make available at low lease rates (Ref. V-4) sufficient land for a VTOL service to their community, the cost of the land should be used for this study. An average value of suburban area land in the corridor area has been estimated at $10,000 per acre. (Ref. V-5). With the parking lot and pad, a minimum of two acres is required. Therefore, land costs would be $20,000.

Total VTOL Small Terminal Cost

The total of the above costs is $312,000 of which the major portion is due to the radio navigation instrument landing system required for use in blind weather. If the site were discontinued, most of these costs are recoverable. Only the parking lot and pad construction costs would perhaps be lost.

STOL Small Terminals

A small STOL facility would still require two runways and a similar amount of land to the major terminal designs. The land costs would be much reduced, however, and a terminal building similar to Figure V-8 would be used.

Cost of Parking Lot, Access Road, etc.

This is taken as being equivalent to the VTOL site at $10,000.

Cost of Terminal Building

Again, it is equivalent to the VTOL building of Figure V-8, at $20,000.

Cost of Runway and Ramp Construction

This cost is taken at $10 per square yard similar to the costs of the major ground level STOL facility. With 1000 foot runways, the runway and taxiway area would be roughly 475,000 square feet for a cost of $530,000. The ramp area costs would be similar to the VTOL landing pad for another $12,000. The total runway and ramp costs are $542,000.

Cost of Communications and Instrument Landing Facilities

This is taken as being equivalent to the VTOL costs at $250,000.

Land Costs

The land area required would be an equivalent two acres for the terminal building, parking lot and ramp plus the land area required for the runways. This is roughly 850,000 sq. feet, or an extra 19.6 acres at $10,000 per acre. The total land cost would be $216,000.

Total STOL Small Terminal Cost

The total of the above costs is 1,038,000 dollars which again has a factor of three over the equivalent VTOL site. The additional expense is solely due to the runway construction and the land area required for these runways. The requirement for runways, even as short as 1000 feet, is a barrier to establishing bus stop type terminals within the corridor. An STOL system would probably be restricted to operating from existing small airports. These are surprisingly numerous in the Northeast Corridor area and many have been specified as terminals in the network studies. The VTOL or V/STOL vehicles can also use these airports at reduced investment costs. Unfortunately, they are not always found in small city centers or suburban areas where they would be most convenient to the traveller.

OPERATING COSTS FOR SYSTEM TERMINALS

Terminal Amortization

In establishing the capital to be amortized, the cost of the land was excluded. This was done because the residual value of the land would be likely to appreciate rather than depreciate. The terminal buildings, ramps, parking lots, runways, etc. would depreciate, and require renovation and repair, and these costs have been used to obtain a yearly depreciation cost. A period of 25 years and a rate of return on investment of 4% have been taken as typical of major U.S. airport amortization. The capital recovery factor with those terms is 0.064.

The system was envisaged as consisting of thirteen large terminals, and 37 smaller ones as indicated in the network studies. Major terminals are VTOL A1, and the ground level, 1000-ft. STOL.

VTOL Ground Facility Amortization

Total capital to be amortized consists of 13 major terminals at $6.3 million each, and 37 small terminals at $0.3 million each. Total capital to be amortized as a running cost equals

$93.1 million. At a capital recovery factor of 0.064 the yearly cost is 5.95 million dollars.

STOL Ground Facility Amortization

Similarly, the total capital to be amortized for an STOL system with 1000 foot runways consists of 13 major sites at 11.2 million each, and 37 smaller sites at 0.81 million each. The total capital to be amortized is 175 million dollars. At a capital recovery factor of 0.064, the yearly cost is 11.2 million dollars.

Terminal Revenues from Concessions

At major airport terminals, between 50% and 60% of the building amortization cost is recovered by leasing space to restaurants, rent-a-car agencies, and various other concessions. This is not true at small airports where the traffic volumes are less. Since this cost sharing is very probable at the major airbus terminals, its yearly effect on the cost to the transportation system should be considered. Applying only 50% of the major terminal building amortization cost gives the following total system yearly costs:

VTOL System - 3.3 million dollars
STOL System - 6.5 million dollars

Elimination of Runway Construction Costs for STOL

Examination of the minor terminals which have been chosen for the example network within the Northeast Corridor shows that 31 out of the 37 are at existing airports where suitable runways already exist for conventional aircraft. By eliminating these runway construction costs, there is a savings of 16.5 million dollars. However, it can be assumed that an equivalent landing fee would be assessed. A similar situation would apply to major airports where perhaps special runways would be required to segregate STOL traffic from conventional traffic and its delays.

Building Maintenance Costs

The yearly costs of operating, cleaning, heating and air conditioning a building have been estimated using a figure of $1.50 per square foot per year. This figure has been obtained from local building managers. It gives a figure of about $50 per week for the small terminal building of Figure V-8, and about $3,900 per week (or $200,000 per year) for the large terminal.

For a system of 13 major terminals and 37 minor ones, the total building maintenance costs would be 2.7 million dollars per year.

Total System Terminal Operation Costs

The minimal operating costs for both systems are:

VTOL System - 6.0 million dollars per year

STOL System - 9.2 million dollars per year

For a system handling 16.7 million passengers per year, costs per passenger handled are:

VTOL System - 0.36 dollars per passenger

STOL System - 0.55 dollars per passenger

or, on the basis of 730,000 vehicle departures per year the unit costs would be

VTOL System - 8.20 dollars per departure

STOL System - 12.60 dollars per departure

The maximum terminal operating costs (when terminal revenues are not included) are:

VTOL System - 8.7 million dollars per year

STOL System - 14.0 million dollars per year

On the basis of cost per passenger, the maximum cost would be:

VTOL System - 0.52 dollars per passenger

STOL System - 0.84 dollars per passenger

The maximum unit cost per departure would be:

VTOL System - 11.80 dollars per departure
STOL System - 19.20 dollars per departure

OPERATING COSTS FOR SYSTEM MAINTENANCE FACILITIES

It is estimated that five airports in the system will have maintenance and hangar facilities. These are spread throughout the system to provide convenient overnight hangarage for the fleet, and allow nightly inspection and maintenance to proceed. As well, complete overhaul facilities for both airframe and engine are required. An estimate of the system investment required for these facilities has been made by examining airline investments in such facilities. Amortization at 5% for 20 years has been used to determine the yearly costs. Equivalent costs would occur from leasing or rental arrangements.

Maintenance Facility Amortization

If a 60 aircraft fleet is assumed, with vehicle dimensions of 150 feet diameter, then a hangarage floor area of 1.08 million square feet would be required. All the aircraft would not be hangared simultaneously, but extra floor space for shops and offices, etc. is required. At $3.00 per square foot, the hangar investments would be $3.24 million.

The overhaul base investment of major trunk airline seems to vary between $5 million and over $100 million. A value of $12 million has been assumed for a 300,000 square foot facility and its equipment, offices, etc.

The engine overhaul base of 50,000 square feet has been assumed to require $2 million, for building, shops and equipment, and engine test cells.

The total investment in maintenance facilities would therefore be $17.24 million. At 5% for 20 years, a yearly capital recovery factor of 0.08 is used to give the yearly costs of $1.36 million.

Building Maintenance Costs

A value of $1.50 per square foot per year is used to estimate the cost of operating, cleaning, heating and air conditioning. The total floor area assumed in the above facilities is 1.43 million square feet. This converts to a yearly maintenance cost of $2.15 million.

Total Maintenance Facility Operating Costs

The maintenance facility operating costs would be $3.51 million per year.

As a cost per passenger, this would convert to $0.21 per passenger.

Expressed as a cost per departure, the value is $4.81 per departure.

Reference VII-1 has estimated the maintenance ground facilities costs for the major airlines as being 31% of direct maintenance costs. For the hypothetical Airbus System producing 62.5 million aircraft miles per year at approximately $0.20 per mile direct maintenance costs, the total maintenance costs would be $12.5 million. Thus the airbus system maintenance ground facilities costs are

$$\frac{3.51}{12.5} \times 100 = 28\% \ ,$$

which compares well with present airline costs on a relative basis.

CONCLUSIONS

The land area and runway construction costs cause STOL terminals to be much costlier than an equivalent VTOL terminal.

Passenger handling and vehicle handling can be accomplished much more rapidly for the Airbus System than present airline practice. This is verified by present helicopter airline practice, and can be extended to larger loadings by use of appropriate ground facilities.

Small VTOL Airbus stops require 2 acres, and can be easily distributed at appropriate points within the corridor at a small investment cost, most of which is recoverable should service be discontinued. The STOL stops will require about 22 acres, plus clear approach areas, and have a large investment sunk into small runways. It will not be as easy to locate suitable sites, nor feasible to move sites elsewhere.

The STOL system indirect costs will be higher than the VTOL system due to the higher terminal costs, and the predominant effect of ground facilities costs on the indirect costs of very short haul air systems such as envisaged for the Northeast Corridor.

References

V-1 "Why do Bridge Costs Vary Between the States?" From a paper presented before the Committee on Bridges and Structures, A.A.S.H.O. on December 10, 1964 at Atlanta, Georgia by F. C. Turner, Chief Bridge Engineer, B.P.R., Washington, D.C.

V-2 International Standards and Recommended Practices, Aerodromes, Annex 14, I.C.A.O. separation standards.

V-3 Information was supplied by two firms of Heating, Lighting and Air Conditioning Engineers.

V-4 "Los Angeles Airways," C.A.B. Exhibits for hearing on permanent certification, June, 1965.

V-5 Unit land prices were supplied by a Boston based firm of land appraisers and represent average values only.

PART VI.

MANAGEMENT INFORMATION SYSTEM STUDY FOR A V/STOL AIR TRANSPORT SYSTEM

VI

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INTRODUCTION

One frequently hears these days that we are at the threshold of a new age: that of "totally integrated management information systems" based upon "real-time computer systems." Since this report is vitally concerned with these topics, it might be worthwhile to discuss briefly the basic concepts that are involved.

First we must define what is meant by "real-time." This term is usually used to describe fast system's response to asynchronous, or random, input requests. The meaning of "fast" systems response in terms of physical time depends on the specific application: a missile launch control system might have to respond within several milliseconds; typical response times for systems interacting with men in a conversational mode would be from one to five seconds; less critical situations might allow response times measured in hours.

The primary virtue of real-time systems is their capability to provide immediate access to large quantities of information and to process it rapidly into the desired form. With this facility, the entire concept of management organization must be reexamined. Lower and middle managers presently spend the majority of their time at routine administrative tasks. A large amount of effort in management, from top to bottom, is spent in obtaining pertinent information and then confirming its validity. Real-time computer systems, if properly integrated into the management information system, can free managers from routine tasks and provide them with immediate access to complete and current information on the operation of their organization. They can use the techniques of mathematical modelling and computer simulation to evaluate quantitatively the expected results of various alternative courses of action.

Real-time computer systems may be justified by the need for their instantaneous response characteristics without regard for cost. Examples of systems of this type occur in the military and missile launch control areas. The SAGE system, a complex of communication-based computers, was deemed essential to the air defense of the United States. The system receives simultaneous inputs from many radar installations and maintains a complete image of the air situation in the continental area. The computers ascertain the existance of hostile aircraft, determine the optimal assignment of defensive forces available to counter the threatening attack, communicate with manned command centers, and produce instructions for the firing and guidance of defensive weapons. The enormity of this problem is indicated by the more than 125,000 computer instructions included in the SAGE system.

During the initial planning stages for the U.S. manned space flight program it became clear that a centralized information system would be necessary for the desired degree of control and safety. These requirements lead to the Project Mercury Real-Time System and its evolution to the current NASA Real-Time Computer Complex at Houston, Texas. This system, composed of five separate IBM 7094-II processors and 269,000 words of on-line core memory, was used for the first time on the Gemini-4 mission.

American Airlines' SABRE reservation system is the largest commercial real-time system in operation. This system is claimed to be earning more than 30% on an initial investment of $30 million, in staff savings alone. Other benefits, such as higher customer convenience, better information for planning, and higher load factors on aircraft are accruing.

Other applications of real-time computer systems which have proved feasible at the present time include time sharing, industrial process control, production cost control, and on-line bank teller systems.

The future for real-time systems appears unlimited. The first of the third generation computers are currently being installed, characterized by low cost integrated or hybrid circuitry, inexpensive random-access storage facilities, and extensive communications capabilities. With this new hardware, real-time processing becomes only marginally more costly than conventional batch processing. Increased configuration flexibility permits either type of processing to occur on one system. Real-time processing can be done during the day shift and batch processing handled at night. Or, with a more sophisticated system, real-time and batch processing can proceed concurrently according to a priority assignment scheme.

Predictions are that the majority of computer systems being installed by 1970 will have real-time capabilities. Beyond 1970, there is every reason to believe that real-time computer service will become available as a utility through the general telephone exchange, almost completely eliminating the need for small to medium sized conventional computer systems.

The Need for an Integrated Management Information System in the VTOL Transportation Network

A well-designed management information system will be essential for the successful operation of a short haul mass transit air system. Extensive processing facilities will be necessary for network scheduling, handling passengers in the terminal areas, and maintaining reservation inventories. The system can be justified on the basis of savings in administrative costs alone. However, there is no effective measure for the added benefits the system will provide in terms of more timely and comprehensive information for managers, less repetitious and uninteresting work for operating personnel, and better customer service.

REAL-TIME SYSTEMS APPLICATION IN THE TRANSPORTATION INDUSTRIES

Airline Reservation Systems

From the first stage of their development, airlines have faced the need for centralized reservation systems. The history of the airlines' attempts to solve this problem reflects the increasing capabilities of electronic equipment over the past few decades. The first improvement upon purely manual reservation systems came in the late 1940's when Teleregister began installing electronic storage aids to work in conjunction with manual retrieval methods. In the mid-1950's, random access disk storage units became available and Teleregister pioneered their introduction to airline reservation systems. The Teleregister systems completely eliminated the need for any manual action in the central record center on agent's requests for information. Agents could request availability status on any flight within a time period of three months to one year into the future, and at the same time make reservations if space was available. Most major airline reservation systems are still of this type, manufactured by Teleregister, Univac, RCA, and IBM.

During 1954, American Airlines and IBM began a joint study on the feasibility of a more comprehensive reservation and management information system. The system was designed to maintain complete information on reservations, flight status, and passenger records, and to provide instantaneous access to this information. In 1958 American Airlines signed a $30 million contract with IBM for the SABRE reservation system, with a projected operational date of 1962. Due to unforseen problems in eliminating errors from the control and operating programs, SABRE did not become operational until late 1963, and did not take over full control of American Airlines' reservations until early 1964.

Current airline reservation systems are of two types: 1) fully integrated systems maintaining complete reservation and passenger record information; and, 2) inventory only systems maintaining records of seats sold on future flights. Three systems are presently in operation possessing the more comprehensive capabilities, all produced by IBM and utilizing large scale computational equipment: 1) American Airlines' IBM 9090 SABRE system; 2) Pan American's IBM 9080 PANAMAC system; and, 3) Delta's IBM 9074 SABRE system. The technical characteristics of American Airlines' SABRE system will be discussed later in this study.

The other type of system comprises the reservation systems for Eastern (Univac 490), TWA (Teleregister Telefile), and United (Telefile), among the larger domestic airlines. A typical installation of this type would be that of SAS, a European airline handling 2.6 million passengers per year. Two IBM 1410 central processors are used, one for backup in case the on-line processor should fail. Four modules of 1301 disk storage are provided, permitting storage of 112 million characters. Rental cost for the central equipment exclusive of leased lines and agent terminal sets is $75,000 per month. Three hundred agents sets, costing $1,500 apiece are included, each with full capability of making reservations between any of the 20 cities serviced by SAS. The system is designed to respond within 4 seconds to agent requests and provides seat availability, reservations, flight information, and hotel reservation service. The backup 1410 is used for time-table production, payroll, accounting, and weekly management reports. Planned for inclusion in the system at a later date are crew scheduling, maintenance planning, and spare parts inventories.

Several airlines are planning to acquire new computer systems in order to expand their reservation equipment into more fully integrated management information systems. Major interest is focused on United Airlines, which is currently evaluating proposals from Burroughs, Control Data, G.E., IBM, and Univac for a total management information system to handle reservations, operations, and accounting needs through 1975. United has a reputation for sound judgment in its purchasing policies, so that the outcome of this competition will bear watching.

Continental, a relatively small trunk airline carrying 1.8 million passengers per year, has recently announced the signing of a contract with IBM for a fairly substantial real-time system. The hardware will consist of two System/360 Model 50 central processors with 262K memories, 300 million bytes of disk storage, 8 to 12 tape drives, 300 agent sets with CRT output facilities, 150 agent sets with hard copy output, and two 1,100 line per minute printers, all at a purchase price of $5 million. The system will provide reservations, schedule preparation, flight planning, maintenance scheduling, and general office data processing.

Railroad Management Information Systems

Progress in real-time system implementation in the railroad industry has lagged behind the airline industry, although the potential benefits here are at least as great. The most advanced reservation system at present time is that of Japaneze National Railways, a Hitachi MARS-101 and MARS-102 computer system. One outstanding difference from typical airline systems is that reservations can be only obtained at ticket offices, where tickets are printed automatically for passengers. Thus, no record at all is kept of passenger names. Domestic railroads do not maintain reservations for coach service due to low average load factors, and apparently still use manual methods to service the small number of first class reservations that are made.

Real-time systems have great promise for improving railroad operation through automatic control. An outstanding application soon to be going into operation is the San Francisco Bay Area Rapid Transit Line. It will be automatically run by a G.E. computer, even to the level of opening and closing the doors.

Since most of the railroads' problems are operational, they can realize great benefits from automating their command and control systems. Simulation of many combinations of demand, schedules, train characteristics, and capital investments will enable optimum operating procedures to be found. Only through implementation of comprehensive management information systems will the railroads achieve the higher levels of service and efficiency necessary to compete effectively with other types of transportation.

AMERICAN AIRLINES' SABRE SYSTEM

The purpose of the American Airlines' SABRE system, as mentioned before, is to provide a range of real-time services centralized around a complete reservation and passenger record facility. For the purposes of this study, SABRE will be analyzed as a practical example in real-time system implementation, hardware design, and programming support.

Implementation

Before we undertake to review the history of SABRE since its conception in 1953, it is necessary to give an idea of the scale of operation in which American Airlines is engaged and to consider the number and types of transactions which the reservation system must process. American Airlines is the third largest commercial airline in the world in terms of passengers carried per year, and fourth largest in terms of passenger miles. In 1960, American carried 8.6 million passengers, and this figure grew to 10.1 million in 1964. The 1964 daily average of 28,000 passengers resulted in an average of 112,000 transactions processed by the reservation system of which 56,000 were reservations, 28,000 were ticket sales, and the rest were of assorted types including messages from other airlines and requests for flight information (FLIFO). Each reservation phone call, or transaction, generated an average of 10 separate inputs to the system. Peak demands have occurred during Monday afternoons in the weekly cycle, when rates as high as 1,700 inputs per minute have been recorded.

SABRE has not always been capable of handling these large loads. Preliminary design work was carried out jointly between IBM and American Airlines from 1954 to 1958. IBM's formal proposal for the system at a price of $30 million came in 1958 and was approved in 1959. By 1960, American had requisitioned experts from within the company to define the functions for the system and had hired 35 to 40 programmers. IBM supplied many programmers of its own to the project. In 1962 the central processors and assorted equipment were installed in a new building at Briarcliff Manor, New York.

The system first went into operation in December, 1962, when Hartford tied into SABRE in dual mode, where the manual system and SABRE were operating in parallel for testing purposes. In May, 1963, New York was added to the system, still in the dual mode. New York comprised 25% of the passenger load and the system immediately encountered problems in keeping up with the input requests coming in. SABRE capacity at that time was one input per 100 milliseconds so that peak loads generated with New York in the system caused saturation. In June 1963, New York was removed from the system and the decision was made to add more core storage to each of the 7090's.

Steady improvement was made to throughput capacity beginning with the increase in core storage in January, 1964. This decreased the process time to 70 milliseconds for the average input. In June, 1964, this figure came down to 60 milliseconds.

Today, 99% of the American Airlines system is converted to SABRE, with the sole exceptions being Mexico City and Toronto. The system can handle an input every 25 milliseconds, and steady improvements are still being made through increased efficiency in the system programs. American Airlines estimates that current capacity is sufficient to handle reservation needs until 1967, when projected growth will cause the system to overload. There are preliminary plans for adding System/360 components to the system to handle the increased loads contemplated for the period beyond 1967.

Hardware Configuration

The basic components of SABRE can be broken down into five divisions: 1) the 7090 central processor; 2) drums, disks, and associated channels; 3) real-time channels and the duplex console; 4) single record equipment and tape drives; 5) the communication network; and, 6) remote equipment. The system is fully duplexed to the extent that a single breakdown in any component will produce at worst only a short period of "down" time before full operation can be resumed. Each city is serviced by at least two terminal interchanges so that if a terminal inter-

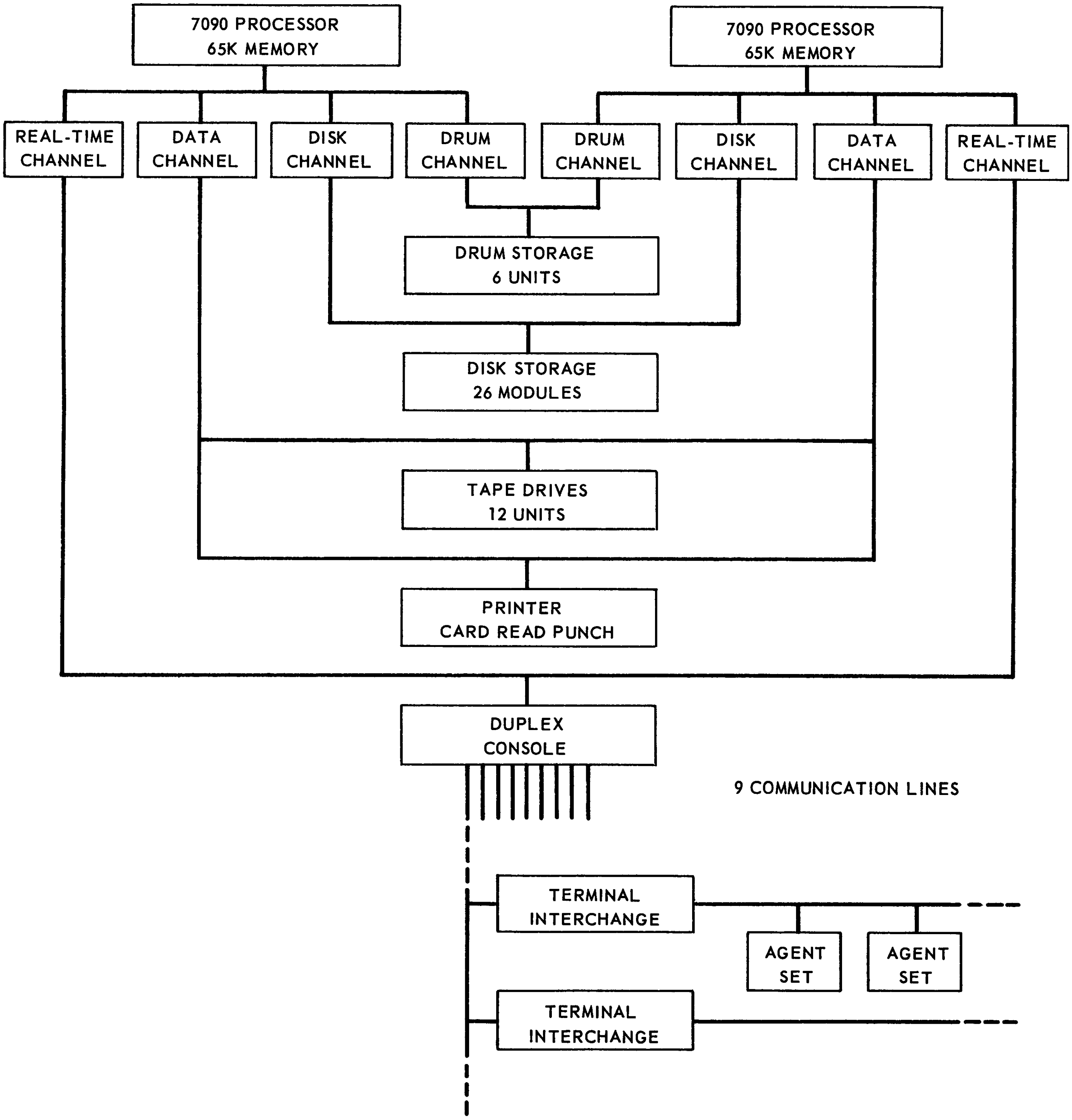

FIGURE VI – 1 ORGANIZATION OF THE SABRE SYSTEM change should fail, the city will not be cut off from the system. Two separate 7090's and associated channels exist so that should the on-line computer fail, the operator can manually shift the off-line computer into real-time operation. All records are stored in at least two separate locations so that a drum or disk failure will not incapacitate the system.

A general idea of the components and their organization into the overall reservation system can be gained from examination of figure VI-1.

Programming Support

The size of the programming task for SABRE can be illustrated by enumerating some of statistics involved. There are over 200,000 instructions in the operational system, of which 20,000 perform 90% of the computation. At least another 200,000 instructions were necessary to perform various stages of testing on the operational programs to assure that they performed correctly. Several hundred programmers were required over the period from 1960 to 1964 to write and debug these massive programs. The system has over 1,000 separate programs, which decompose into the following types: a) Control Programs supervising system operation and acting as an interface with the I/O equipment; b) Operating Programs concerned with satisfying the functional requirements of the airline reservation system; and c) a wide variety of special purpose programs such as assemblers, loaders, dump routines, debugging aids, etc.

We will analyze the programming support for SABRE in three stages. First, the concepts of multi-programming and dynamic program relocation will be discussed. Secondly, the hierarchy of record storage will be explained, along with the methods used for addressing. And, lastly, the debugging aids and testing environment will be described.

Real-Time Environment: Multi-Programming and Dynamic Program Relocation

Under the conventional batch-processing mode of operation each program is read into memory and processed serially. If SABRE were to use this mode, it would have a processing capability of one input every 385 milliseconds. The reason for this low speed is that although each input requires only 21 milliseconds of central processor time, the average input request (remember that full reservation transaction might involve 10 input requests) requires 3.9 accesses to drum storage, and 2.5 accesses to disk storage.

In order to overlap data accesses with central processor computing to the greatest possible extent, the multi-programming technique is used. In this mode, several jobs are simultaneously available in core for execution. Strictly speaking, only one job is being executed at any given instant, but if that job should reach a point where it can no longer proceed, such as the case when the results of a file seek operation are needed, another partially processed job may be reactivated, or a new job started. Control at this point is given to the supervisor program, which determines the next task to perform, while the current job lies dormant until its input/output requirements have been satisfied.

When a complete input message has been received by the system for processing, control is given to the first of a series of operating programs which must be executed to satisfy the request. The operating program is brought into core storage from its permanent residing area on drum or disk. Since the organization of core storage is dynamically changing over a period of time due to the multi-programming mode of operation, the programs must be in a relocatable form so that the channel hardware can load the program into any free memory space. This technique is not as complicated as the fully dynamic storage allocation schemes used in time-sharing applications, where programs are continuously swapped in and out of core to make room for other programs desiring to use their share of time for computation.

Storage Considerations

One characteristic of multi-programming is that a particular data record may be required for use by more than one job at the same time. A restriction is required whereby a record accessed for updating purposes may not be accessed by a second job until the first job has refiled the record. Similarly, core storage areas used in common by different jobs cannot be expected to remain unchanged by a job which has temporarily relinquished control.

List structures are used for allocating core storage in the SABRE system. A list structure consists of a set of fixed-length blocks of storage which are chained together through pointer words at the head of each block, containing the core address of the next block in the chain. Starting at the first word in a list, it is possible to sequence through the entire chain, even though the blocks may be scattered anywhere throughout memory.

The drum and disk files are organized with the following major aims:

1) to provide a means for locating records with a minimum of time and programming effort;
2) to take advantage of special characteristics of the processor, channel, and storage device; and
3) to enable the file to be easily loaded, maintained, and controlled.

The basis of the entire SABRE system is inventory of seats on future flights. To provide rapid access to information on flights departing in the near future, inventories for a certain number of days, usually 15 to 30, are maintained on the drums. The exact number of days of future flight inventories is adjustable depending on the amount of storage available. Flight inventories for the rest of the year are kept on disk.

Two gross indexes to flights are maintained on drums, one for flight inventories stored on drum, and the other for the flight inventories stored on disk. Each gross index consists of 1,000 consecutive words, each location referring to a flight number ranging from 000 to 999. These words contain the address of a fine index which is stored on the same type device (drum or disk) as the inventory to which it refers. The fine indexes are composed of one-word records, each pointing to an inventory record for a flight on a certain date.

Inventory records are constructed when the first reservation for a flight-date is made. All inventory records are stored on disks when they are created. If they belong on the drum they are placed there by the nightly file - maintenance program. The nightly maintenance program includes a cycling procedure to transfer one future day's inventory records from disk to drum and to adjust the corresponding gross and fine indexes.

A large number of requests are merely for availability information for one to four seats on a given flight-date. To obtain this information from the flight inventory would require three separate file accesses, including one access to the gross index and one access to the fine index. To reduce the time required for availability information, special availability files are maintained. As with inventory, a certain number of day's records are kept on drums, and the remainder on disks. In these records one bit is used as an availability indicator for the required number of seats.

Whenever a reservation is made, a passenger's name record (PNR) is processed and stored by the system, based on information entered into the terminal set by the agent. Numerous references to the PNR are necessary after the PNR has been stored: 1) preparation of flight manifests; 2) processing waiting lists of customers; 3) entering flight schedule changes; 4) changes in passenger itineraries, including cancellations; and, 5) changes in passenger status or other passenger information. Since reservations may be made up to a year in advance, a large number of PNR's must be kept available for immediate access. A pool of available disk storage is maintained with directories keeping track of available space.

Requested PNR's are addressed through a gross index followed by lookup in a fine index. The address of the gross index for a particular flight on a given date is computed from the flight number and date. Each flight-date record in the gross index consists of: 1) pointers to alphabetic groupings contained in the fine index; 2) a pointer to the waiting list storage area; and, 3) a pointer to an extra section for the flight, if there is one. The fine index contains compressed information on each passenger name and pointers to the pertinent PNR's.

The gross index for the next four day's flights is maintained on the drums, while the gross index for the remaining days is kept on the disks. The nightly job-maintenance program performs the required cycling actions required to maintain these records.

Program Testing

Programs for SABRE pass through several stages of testing before entering the system on a fully operational basis. Programs are first tested with an environment simulator system which can be run on a standard 7090. It provides a simulated control program, several program debugging tools, and the facilities for testing with standardized input data.

Following this first stage of testing a program progresses to an environment which is relatively close to normal real-time. The standard control program is modified only in that output is not sent to the real-time channel but stored on tape for later analysis. Programs are also not allowed to reference the real-time files, but instead reference a set of standard records preloaded on the spare disk module. Testing at this level proceeds on the standby machine during real-time operations.

The operational programs should be reasonably error-free by the time simulated real-time tests are complete. However, errors may remain that result from situations not anticipated, such as interaction with other programs, as well as plain oversights in previous debugging. During the early stages of programming for SABRE, the operation of the entire system was simulated in volume testing at this stage. Field tests were scheduled concurrently for the purpose of checking out the communications network. Since the data was entered by individuals, the tests also provided a check on the ability of the system to cope with human errors.

Parallel operation was the final step prior to the system's assuming the entire reservation load. Parts of the reservation system were placed in operation gradually with accuracy checks being provided by the simultaneous manual processing.

Evaluation of the SABRE Project

The first comment which must be made on the SABRE system as a whole is to acknowledge the pioneering activity which produced the smoothly operating reservation system that exists today. SABRE provided invaluable experience for IBM, American

Airlines, and the entire computer and airline industries on the design and implementation of large-scale real-time systems.

However, there are problems in the application of the SABRE system. The pioneering approach is rarely the least costly, and SABRE is currently costing American Airlines $6 million a year for machine depreciation, maintenance, rentals, and pro-rated programming costs. Despite the fact that the entire SABRE system could now be duplicated for approximately $2.5 million per year using IBM System/360 components and programs, American Airlines is so tied down with their present system that they cannot even go to the 7094's due to channel timing considerations. All of the more than 200,000 instructions comprising the SABRE programs were coded in machine language. This means the entire set will have to be scrapped when American decides to go to the more powerful but incompatible third generation hardware.

American Airlines is not neglecting the trend toward more comprehensive management information systems exemplified by the intentions of United Airline in this area. However, American's flexibility of action is seriously impared by their stake in the costly and complex SABRE project. The fact that the system has indeed satisfied its design goals with 1960 technology may prevent American from realizing the full benefits of third generation computer technology and the new capabilities of management information systems.

PRELIMINARY SYSTEMS DESIGN - VTOL AIR SYSTEM 1980

It is far too early to assess hardware and software requirements and to specify a preliminary systems design in a manner which can be defended as realistic for a period 15 years in the future. It will be our goal here to produce specifications which are best-estimates of the situations likely to be encountered in 1980. These estimates incorporate detailed information on several operational real-time systems, information on certain airlines' plans for satisfying their information system requirements for the future, and results of studies on network organization and passenger demand to be encountered in the Northeast Corridor for 1980.

System Environment

Several assumptions are made concerning the environment in which the management information system will function:

1) The transportation vehicle will have vertical take-off and land capability, cruise at speeds approaching 500 mph, and carry 80 passengers;
2) load factors and annual vehicle utilization will be high: 60% and 3,000 hours, respectively;
3) 50 terminals will be located in major city areas, suburban areas, and major airport locations;

4) since a decision cannot be made at this time as to whether or not reservation service should be offered, both cases will be considered.

Network flow studies have indicated expected loads on the order of 20 million passengers per year, if ticket prices can be kept competitive with current modes of air service. For the network of terminals considered, this would result in an average of roughly 2,000 vehicle take-offs per day, with the average passenger going 180 miles with a few intermediate stops on the way. A chart showing the breakdown, by terminal, or originating passenger-per-day statistics and vehicle take-offs per day is included in Appendix I.

It should be noted that plans for the management information system will constitute a major part of the design for the overall operation of the network. Remote displays and agent sets must be included in terminal designs, and space provided for the central computer facilities. The eventual operating mode of the transportation system will be determined on the basis of optimization studies, simulation, and trial and error.

Functions

The operating structure of management in 1980 will be far different from that which presently exists. Most of the repetitive and routine functions of lower and middle management will be assumed by the computerized management information system. Operation of a short-haul mass transportation system will be maintained with a minimum of administrative and supervisory personnel. Top management will work hand-in-hand with systems analysts and computer experts in forging the most efficient operating modes for the network. With specially trained personnel stationed at the points of man-machine interface, the management information system provides the structure of the transportation system's operating organization.

The next few pages idealize the functions of the totally integrated management information system indicated in Figure VI-2. Practical considerations of implementation will be taken up in succeeding sections.

Boarding Control

Boarding control entails all the operations necessary to maintain reservation records and to supply information for handling the passenger, whether he has reservations or not, from the time he enters the terminal building to the time he is aboard the aircraft with a completely processed ticket.

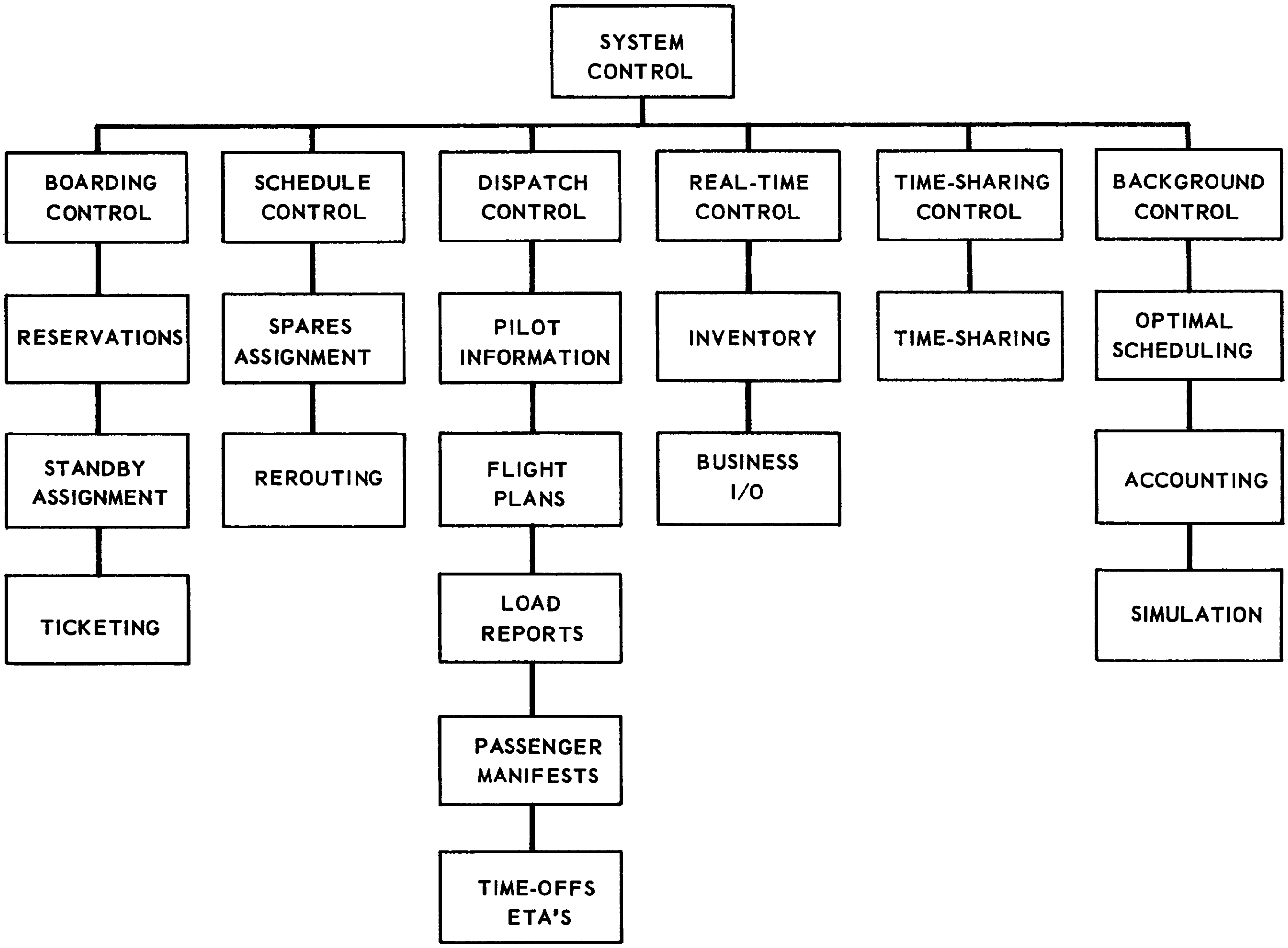

FIGURE VI – 2 ORGANIZATION OF THE 1980 SYSTEM FUNCTIONS

Reservations, if this service is to be provided, would be available for a surcharge that would be established to cover the cost of this extra processing. Since the passenger would have a choice of paying the surcharge if he desired reservations to assure that he had a seat on a certain flight, there appears to be no reason for not providing this service. An argument for providing reservation is that during peak demand conditions most passengers would make reservations to insure space, thus raising the average price of the tickets through the entire system, thereby encouraging off-peak travel. Without reservations, there would be massive passenger jams inside terminals during peak conditions, where the passenger would have to wait for hours in long lines in order to get a flight.

Complete reservation service is a complicated matter, as can be seen from the description of the SABRE reservation system in a previous section. Inventories of remaining seats on flight segments must be maintained. Passenger name records must be kept for the purpose of notifying passenger of changes in waiting list status or flight schedules. An optional, but extremely desirable feature is connection to other airlines' reservation systems, so that a passenger may make all arrangements for his trip with one phone call. Miscellaneous information on passengers is also maintained, such as special handling necessary for invalids.

For the 1980 Air Bus system it is expected that most passengers will undoubtedly prefer to use the lower-cost standby type of service whereby they report to terminal areas and are boarded on a first-come first-served basis, with the wait list handled by the load control program of the computer. This service also will require extensive communications network and data storage facilities to gather boarding, traffic, management data and transfer it directly to central records. In an "air shuttle" type of operation, all passengers get on at point A and get off at point B. However, the VTOL network will be very complex, with several intermediate stops occurring on many flights. A passenger getting on at point A on a flight to point D with intervening stops must be assured that his seat is available all the way through, and that he will not be bumped off by someone with reservations from C to D. It is also desirable to relay space available information to the next terminal as soon as a flight departs, and transfer load control to the traffic agents at the next station so that they may begin processing the standby traffic.

A centralized system for handling the integrated reservation - standby service is an obvious necessity. There are added benefits to be derived from such a system. The demand and utilization statistics produced for the system on a real-time basis can be highly useful for planning purposes such as scheduling extra flights. A completely floating schedule based entirely on instantaneous real-time demand appears to be unfeasible for reasons of the desire to maintain high load factors and good vehicle utilization by schedule planning, and the need for published timetables to assist the traveller in planning his journey, and also from the considerations of crew assignment and vehicle maintenance. The boarding control system however, provides a good source of information for feeding back into schedule planning on a fairly short time basis.

All passenger contacts with the management information system will occur through boarding control. Terminal displays will be connected with and automatically controlled by the centralized system. Two primary types of displays will be provided: 1) flight status displays giving information on arrival and take-off times, and comments such as weather conditions; and, 2) boarding notices for passengers with reservations and passengers on standby status who have been assigned seats on flights.

One possible mode of handling calls for reservations or information would be the following: a) when the computer first answers the phone, an audio response device would give instructions for the input operation; b) the caller would use the buttons on his push-button dial phone (assuming everyone has one in 1980) to input the desired flight segment, his name, etc.; c) the computer, every time a response was required would output another message from the audio response device. This mode, although increasing the computer load, would almost completely eliminate the requirement for reservation and telephone information agents and their agent sets. These two components, incidentally, make up approximately 90% of the total operating cost of present airline reservation systems.

Ticketing can proceed on a completely automated basis. When a passenger makes reservations, he has the option of having the ticket sent directly to him or picking it up at the terminal. Information would be imprinted on the ticket in machine-readable form so that when the ticket is collected it can be processed with no additional conversion. The telephone exchange system in 1980 may have such comprehensive capabilities that banking and credit accounts may be controlled directly over the telephone. Certain security procedures will be necessary, such as secret "passwords" permitting access to accounts.

Schedule Control

Some flexibility will be provided for scheduling during rush hours. Information for boarding control can be used in assigning spare aircraft to network links with unexpectedly high passenger loads.

Since space on the terminal landing area will be limited, landing pads and gate assignment will be handled on a real-time basis. Since the entire network interacts in the case of unavailability of landing pad during near-capacity operations, a centralized computer program can determine a course of action which will result in minimum disruption of service.

Vehicle breakdown and bad weather conditions can also cause problems in maintaining scheduled service. With a centralized information system and the availability of high-powered computer processors, optimum solutions to the problem of routing can be determined to minimize passenger inconvenience. With the high vehicle operating costs when empty, this approach is deemed necessary to obtain both high vehicle utilization and passenger load factors, i.e. system efficiency. Very detailed statistics on passenger flows in the network which are necessary are gathered directly from the boarding process.

Dispatch Control

Before a pilot can take off for a flight, he must have certain information at his disposal and transmit several documents to the authorities. The pilot must evaluate the weather predictions for enroute conditions and calculate the loading of his aircraft. He must then transmit the official flight plan and load reports to the authorities.

The pilot's tasks can be considerably simplified by services from the centralized information system. Before taking off, he receives an up-to-date report on weather, air traffic conditions, and destination terminal conditions for the flight. His flight plan can be prepared automatically from data gathered on scales located under the aircraft as it is being loaded. As soon as he lifts off, he can report the time and his estimated time of arrival at the next stop so that this information can be relayed down the line. He may want to revise his ETA during the flight, but at the short stage lengths contemplated this should rarely be necessary.

A definite CAB requirement is that a passenger manifest be prepared for each flight and stored for a period of time presently set at 60 days. This requirement will be handled by updating reservation and standby space assignment records as the vehicle is loaded. At night the information will be dumped from the random access storage onto magnetic tapes for storage for the required period of time.

Air Freight

In order to maximize the utilization of the VTOL network, a portion of the vehicles would be of a convertible passenger-cargo variety. During off-hours, particularly at night, vehicles would carry freight at high speeds from city center to city center. The centralized information system would provide reservation and scheduling services for freight handling similar to those provided in the case of passengers.

Optimum Scheduling

In the era since the end of the second world war, the simultaneous development of optimization techniques such as linear programming, dynamic programming, and network flow optimization, and high speed computing machinery has made possible great advances in the area of efficient scheduling of complex operations.

Efficient scheduling in the VTOL network will contribute to both better passenger service and also higher profit in operation. On the basis of feedback information from boarding control, long term scheduling can be accomplished in an optimum fashion. Seasonal changes in scheduling and even changes in network topology, e.g., summer resort area terminals, can be accomplished smoothly and efficiently.

Once an operating flight schedule is established, the aircraft fleet and crews must be assigned to provide the means of carrying it out. Aircraft must be maintained. Crews cannot fly more than a certain number of hours per day and like to get home once in a while. Thus, a large scale assignment problem must be solved. Currently, this is done on a rule-of-thumb and experience basis. There does appear to be promise of finding optimal solutions through development of applicable computer algorithms.

Management and Accounting Functions

Progressive business firms have established the practice of holding frequent management briefings on the current status of operations. This will be a desirable practice in the VTOL network and will be facilitated by the services offered by the management information system. Up-to-the-moment summaries of operating statistics will be available in several forms, ranging from printed reports to real-time graphic displays. Discussion and decision-making among top management will be facilitated by rapid access information retrieval and simulation capabilities of the real-time computer system.

Marketing will be an important activity in the business operation of the VTOL network. Such factors as ticket price, advertising, vehicle characteristics, frequency of service, and passenger demand are related in a very complex manner. Marketing studies in simulation and projection will be required to achieve a desirably balanced type of service. The marketing department should be frequent users of a time-sharing computational capability offered by the management information system.

Conventional business functions will be handled in much the same fashion as today. Accounting procedures such as ticket processing and payroll processing can be accomplished during the off-hours of system utilization. Real-time activities such as inventory control can be assumed along with the other real-time activity going on in the system.

Performance Requirements

In order to allow for variation from predicted utilization of the VTOL network, and to allow for the possibility of initially going into operation on a smaller scale basis and then growing progressively larger with time, a range of performance will be considered in specifying the implementation of the management information system. In this study, four levels of performance are investigated, corresponding to network utilizations of 5, 10, 20, and 40 million passengers per year.

Detailed analysis into the computer system requirements, as a function of passengers processed per year and management utilization of the system, is not possible within the confines of this study. Needless to say, this analysis would have to be done before considering the actual implementation of the system.

General considerations in specifying performance, storage, and I/O requirements of the system are as follows:

1) Sufficient processing power must be provided such that the system is not overloaded by the anticipated computational demands of the totally integrated management information system;
2) Sufficient random access input/output capability must be provided such that queues do not form to cause waiting times longer than the specified system response time (1-3 seconds);
3) Random access storage capability must be provided capable of retaining all records needed on a quick - access basis; and
4) Satisfactory numbers and types of remote terminal devices must be supplied to handle the anticipated input/output requirements.

An estimate of the processing requirements for real-time functions associated with passenger processing and vehicle takeoffs was obtained from analysis of the SABRE system. In the VTOL system, each passenger in reality must have a reservation when he boards the aircraft, whether he explicitly buys one or not. Thus, computational loads per passenger should be similar to those experienced by SABRE, e.g., peaks of 1,700 inputs/minute for the 10 million passenger per year scale of operation. As stated earlier, each input requires 21 milliseconds of 7090 computer time and 3.9 drum accesses and 2.5 disk accesses, on the average.

The real-time load approximated by the SABRE statistics was estimated to be roughly 25% of the central processor load and 75% of the random access I/O load for the total system.

A balanced hierarchy of random access storage was specified for each of the four systems in terms of core, drum, and disk. A compromise between cost and capacity was necessary for each level of system performance.

IMPLEMENTATION STUDY - 1965

State-of-the-Art

At first examination, evaluation of current state-of-the-art in computer technology seems to be an impossible task. The variety of equipment which is available is so sizable that even brief examination of all components would result in several volumes of material. In point of fact, such volumes do exist, prepared by "experts" for the customer who desires unbiased information on available hardware.

Several dozen companies are involved in the actual production of digital computers in the United States. Foreign manufacturers will be of little interest here because in most cases their state of technology lags behind the U.S. The major computer producers, in order of value of installations as of 1964, are: 1) IBM; 2) Sperry Rand Univac; 3) RCA; 4) Control Data;

5) NCR; 6) Burroughs; 7) G.E.; and, 8) Honeywell. Smaller manufacturers, with roughly 5% of the market, include: Scientific Data Systems, Digital Equipment Corporation, and Advanced Scientific Instruments.

Recently, starting with IBM in March, 1964, several large manufacturers have announced new "third generation" compatible families of computers. Compatibility, in the computer sense, means the facility of running a machine language program on any member of the computer family, as long as sufficient storage space and input/output equipment are available in each case. In different words, compatibility means that each computer within the family has the same instruction set and data handling procedures. Upwards compatibility means that a program which runs on a smaller model in the family can also run on larger models, but not necessarily vice versa.

"Third Generation" as used in the electronics industry, pertains to the type of circuits used. There appear to be substantial cost and speed advantages in using these micro-miniaturized circuit components. Integrated circuits have all components, including transistors, diodes, resistors, and capacitors, combined in one small integrated unit. Hybrid circuits, for reasons of flexibility and speed, have micro-miniature transistors and diodes incorporated separately from the other components.

A brief run-down on the characteristics of major compatible computer families is as follows:

IBM	System/360, a line of completely compatible computers with hybrid circuitry covering a range of performance from small punched card machines to the largest and most powerful scientific processors.
RCA	SPECTRA 70, a line of upwards compatible computers, the smaller models utilizing conventional sized circuits and the larger models utilizing integrated circuits, covering a range of performance from small punched card to medium sized general purpose processors.
Honeywell	SERIES 200, a line of upwards compatible computers, utilizing some integrated circuits in conjunction with conventional types, with a range of performance similar to RCA's SPECTRA 70.
G.E.	400 Series, a compatible family of small to medium sized business computers, with conventional circuits; 600 Series, presently consisting of one central processor with two memory options, utilizing conventional circuits, and in the large scientific performance category.
Control Data	3000 Series, with upwards compatibility within the 3100-3200-3300 set and the 3400-3600-3800 set, using conventional circuits and possessing medium to large

scale scientific performance; 6,000 Series, with complete compatibility, conventional circuits, and extremely high performance.

Software, or programming support, will reach new dimensions in the third generation computer families. All manufacturers are promising sophisticated "operating systems," programs necessary to monitor CPU activity, supervise job to job transitions, and control input/output operations. Compilers for both scientific and business high-level languages will be supplied. In most cases FORTRAN is the scientific language supported, and COBOL the business language. In addition, machine language assemblers, with extensive features easing the programmer's task are included in the operating system. Finally, assorted special purpose routines, such as sort programs and scientific subroutines are provided.

Selection of IBM System/360 for the 1965 Implementation Study

IBM System/360 was selected as the best suited for implementation for the following reasons:

1) Hardware - System/360 is the only family of computers offering complete upwards and downwards compatibility over the range of performance which may be necessary for the VTOL network. System/360 includes by far the greatest variety of peripheral equipment. A particularly

desirable storage device, the 2314, is available from no one else. It uses removable disk packs so that two copies of records stored on disk do not have to be maintained for reliability purposes. In cases of 2314 unit failure, there is almost no likelihood that information on the disk itself will be harmed. Thus, all that needs to be done is to manually move the disk packs to a spare 2314 unit in order to regain full operation. System/360 also offers a good assortment of remote terminal devices, including the low-cost 2260 visual display device.

2) Software - System/360 programming support is extensive, including sophisticated operating systems, compilers, etc., and several new advancements. IBM is providing complete support for time-sharing installation and airline reservation systems. This means that the great burden of programming necessary to support the management information system would be supplied by IBM. In addition, IBM is developing a new high level language for System/360 with such extensive facilities that machine language programming will be required in only rare cases. This language, called by the various names NPL, MMPL, and lately PL.I, would considerably simplify the task of programming the functions not supplied by IBM.

3) Cost/Performance - As can be seen from Figure 5.1, the system/360 family of Models 40, 50, 65, and 75 are exceeded in cost/performance measure only by the Control Data 6000 Series (the 6400 is the only 6000 Series machine which has "low" enough performance to fit on the chart).

The choice of System/360 for the purposes of this study was clear-cut. A mundane but perhaps overruling consideration was the availability of detailed information on System/360. Large quantities of printed matter were gathered on other systems, but sufficient details on performance characteristics and cost data were simply lacking in several cases and barely adequate in others.

System Designs for 5, 10, 20, and 40 Million Passengers/Year

The preliminary performance requirements for the real-time systems have been specified. These were broken down into CPU power, random access I/O capability, random access storage requirements, and remote terminal requirements. In this section we first describe the hardware components that will satisfy these requirements for the four systems. Then the general characteristics of the computer models used to simulate these systems are discussed. Finally, individual characteristics, such as

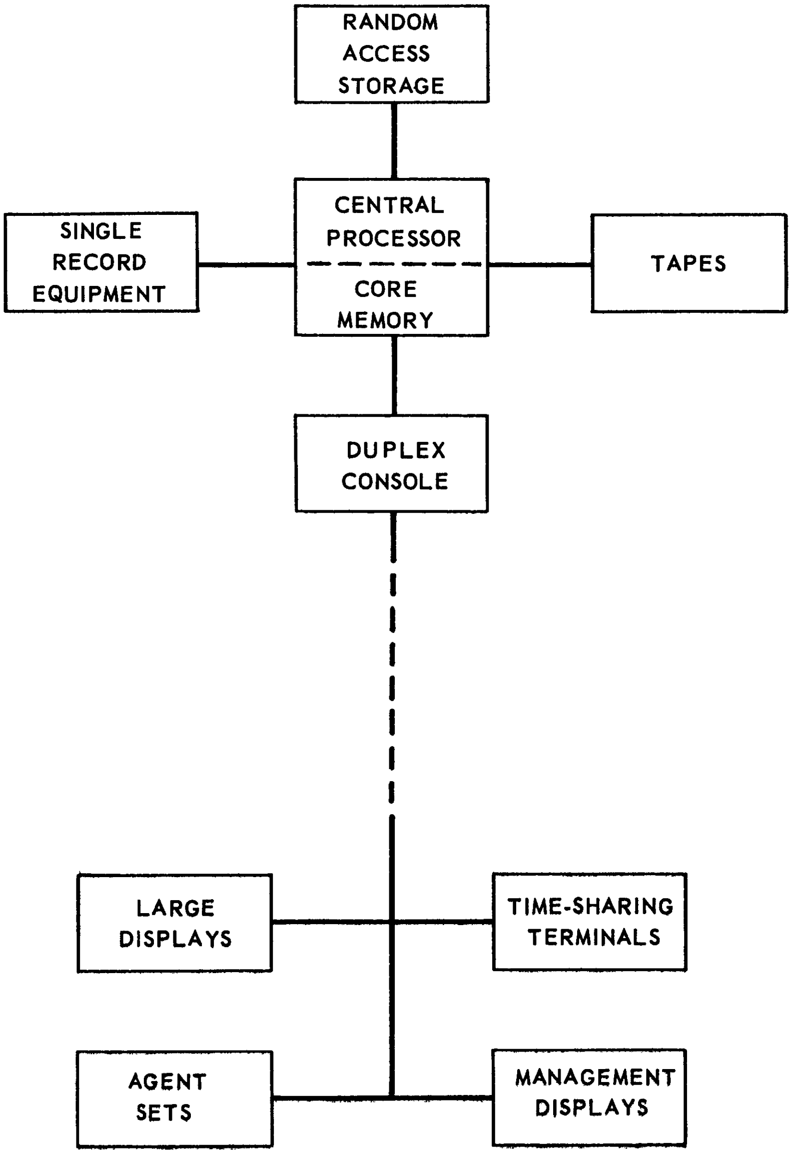

FIGURE VI-4 PHYSICAL ORGANIZATION OF 1980 SYSTEM organization and cost, are given for each system. The general organization for the systems is given in Figure VI-4.

Components

Central Processor. There are two major considerations in specifying the central processor configuration: 1) Sufficient computational power must be provided for total peak requirements; and, 2) failure of a CPU cannot disable the central real-time functions. These considerations indicate the need for a multi-computer, multi-memory system.

Several central processor types are used in the system designs. The System/360 Model 50, with a memory cycle of 2 microseconds, has approximately the same computer power as the well-known IBM 7090. The model 65, with a memory cycle of 750 nanoseconds, is roughly four times as powerful as the Model 50. The time-sharing version of the Model 65, known as the Model 67, has several additional features, described in the previous section on 1965 state-of-the-art, which make it particularly suited to multi-computer multi-memory applications.

Random Access Storage. One requirement for random access I/O is that for a device with considerably more capacity than core storage and with an access time of a few milliseconds. The 2301 drum is the highest performance random access storage unit

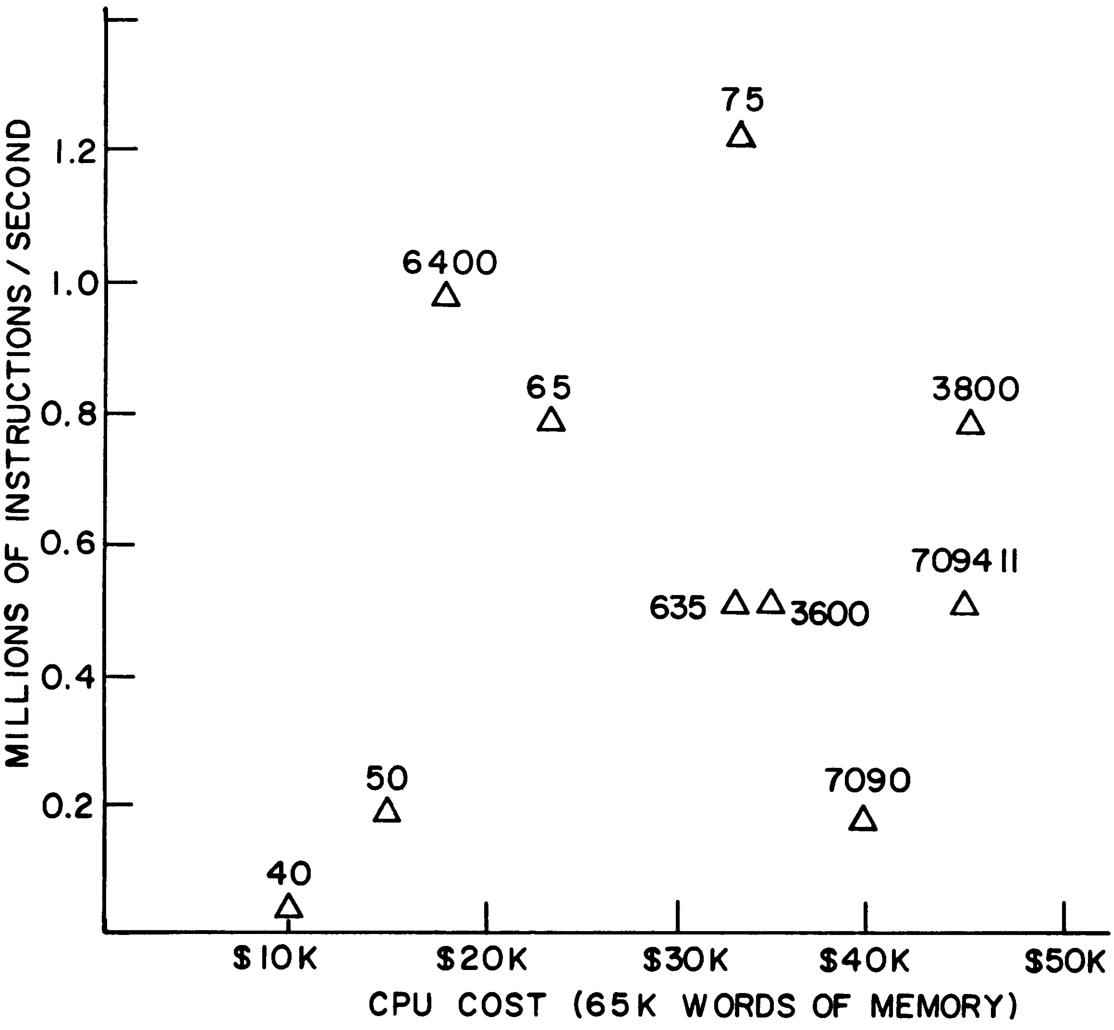

FIG. VI-3 COST/PERFORMANCE FOR CPU'S OF INTEREST in the System/360 inventory at the present time. The 2301 has a capacity of 4 million bytes of storage, with an average access time of 8.6 miliseconds. This drum also has a very high data transfer rate of 1.2 million bytes per second.

Perhaps the most severe requirement in the random access category for the real-time system is that of providing massive data storage with high throughput capacity. In this case it is not particularly important that the average access time per record be low, as long as a number of accesses can be going on in parallel, so that the average overall frequency of access is high. In the past this mode of operation has been achieved in two ways: 1) provision of several "modules" of disk storage, with each module serviced by an access are; 2) provision of one disk module, but with many arms servicing this module. The first method has been extremely costly in the past - SABRE has this type of storage, with 24 modules of disk, each serviced by its own access arm. A good example of the second method is the MD20, a disk module storing 200,000 characters and serviced by up to 16 independent access arms.

The recently announced IBM 2314 direct access storage facility is well suited to application in high storage capacity, high throughput applications. This unit contains nine separate disk drives and associated access arms, where 8 are on-line and one is a spare. The actual disk storage devices are of the "disk pack" variety, which can be removed from the drive and interchanged at will. The 2314 stores more than 200,000 bytes of information. The access arm has an average seek time of less than 75 milliseconds, very low for a large capacity random access file. The disk rotates once every 25 milliseconds, so that once an arm is positioned there will be an average rotational wait time of 12.5 milliseconds until the desired record passes under the read-write head. A simulation model of the 2314 (see Appendix V.1) indicated that it could service an access request every 14 milliseconds, on the average. This is outstanding performance for a unit storing 200 million bytes at relatively low cost.

Perhaps the most important characteristic of the 2314, as mentioned earlier, is the interchangibility of the disk recording surfaces. Besides allowing unlimited off-line storage, the interchangibility feature halves the on-line storage required in the system and decreases the number of accesses which have to be made. Without interchangibility, when a disk unit fails there would be no way to retrieve the information stored there. In the case of the 2314, if a single disk drive or access arm fails, there is a spare drive for such occasions. If the entire unit fails, the disk packs containing all information stored there can simply be shifted to a spare 2314. Only in the rarest of occasions will the failure of a 2314 cause data to be destroyed on the disk pack, so that system records only need be stored in one place, and no duplicate copies maintained. Also, since there are no duplicate copies kept, the average number of "write" operations on the disks will be significantly lower.

There are several factors to be taken into consideration in attaching the 2301 and 2314 storage devices to the central processor. The 2314 contains all necessary control units, but the 2301 drum requires a separate control unit, the 2820 drum control. The 2820 can control up to four 2301 drums, if this is desired. Control units must be connected to the CPU with input/output channels. Since both the 2314 and 2301 are high performance devices, high speed "selector" channels must be used. On the Model 50 processor, there is provision for attaching only one 2820 drum control. On the Model 65, up to 8 drum controls can be attached to a total of 6 channels for each CPU. In the more flexible Model 67 configuration, up to four channel controllers with up to 24 selector channels and 32 drum controls are permitted. There are no practical limitation on the number of 2314 units which can be attached to the systems considered.

There is an interesting trade-off involved in the mode of channel operation. Usually a channel is freed to perform other operations during the time an access arm on a disk unit is repositioning. However, during the rotational delay time on both drum and disk the channel is usually unavailable for other uses. In the SABRE system, a different mode is used in order to make use of the channel during the time a surface is rotating under a read-write head to the proper position. This mode, called "record-ready," permits the channel to transmit data from other devices during rotational delay time. A millisecond or so before the proper record comes under the read-write head, the control unit attempts to seize the channel. If the channel is free at that instant the control unit can go ahead and transmit the data. If the control unit is busy, the control unit must wait another revolution and try again at that time. Since typical rotational delay times would be on the order of 10 milliseconds and average data transmission times more like one millisecond, the channel can be used more productively in this mode.

Apparently System/360 channel organization does permit this "record-ready" mode of operation. The cost of increased channel utilization, however, is the loss in performance of the random access devices attached to the channel, due to the occasions when transmission is denied because of the channels being busy. Cost/performance analysis indicates that the two different modes, "record-ready" and standard, are roughly comparable by that measure.[1] Since there is no cost penalty in providing a channel

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[1] As a typical example, two 2820 drum controls serviced by separate channels in the regular mode would cost $13,600 in monthly rental and would have capacity for an access every 4.5 milliseconds. On the other hand, two 2820's serviced by one channel in the "record-ready" mode would cost $12,100, but due to the performance liability of this mode

for each 2314 and 2820-2301, this mode is used in the four systems designs in order to minimize the average wait time in queues.

Operator Consoles. Advancements in console devices will make the computer operations' tasks much easier. The 2250 display console provides a CRT screen for printed message and other displays. The screen can display up to 52 lines of 74 characters and can plot points and curves for the purpose of providing the operators with information on system operation. The 2250 console also contains a keyboard for inputting commands to the system, and a set of controls for such functions as stopping and starting the system. The model 67 also has a set of controls which define the choice of configuration of CPU's, memories, and I/O devices for the particular job

Conventional I/O. The four systems considered will all have provision for conventional forms of input/output. The 2540 Card Read Punch reads cards at 1,000/minute and punches at 300/minute. The 1403-2 Printer prints at a rate of 600 lines/minute, and the 1403-N1 prints 1,100 lines/minute. Conventional tape drives for off-line storage are represented by the 2301 tape unit,

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the capacity would be an access every 5.1 milliseconds. This reduction in performance is calculated by assuming the channel will appear busy to each 2820 control unit 1/9 of the time, so that the expected delay factor is a geometric series $1 + 1/9 + 1/9^2 + \ldots$, equal to 9/8. Thus the reduction in price for the "record-ready" mode is almost exactly offset by the resulting reduction in performance.

reading and writing 90,000 bytes/second. An optical character reader will be necessary to process tickets. However, the type of optical reader which will be necessary cannot be determined at this time.

Remote Terminal Devices. The major portion of system cost is not in the central processing facilities, as might be expected, but in the large number of remote I/O devices which must be provided. To service the needs of the large number of personnel using the system, including reservation agents, check-in agents, system programmers, and individuals from the accounting, marketing, and management areas, a variety of devices will be necessary.

A particularly ingenious terminal device is the recently announced low-cost 2260. The device includes, in one small attractive unit, a display screen and an input keyboard. Data input on the keys appears instantly on the screen for verification and can be sent as a message to the central processor. Responses in the form of output messages appear on the screen after a time interval of several seconds. "Hard copy" output, as will be necessary for printing tickets, time-sharing operations, etc., is provided by the 1977 terminal device, basically an input/output typewriter with some special purpose buttons.

Large sized displays for passenger information and management briefings cannot be specified without getting into the designs of terminals and office buildings. They will probably be in the form of arrays of character tubes and projection screens for high-precision CRT displays.

Performance Evaluation

There are two major considerations involved in assuring satisfactory system performance: 1) system response time; and, 2) system throughput capacity. These two interacting factors are difficult to predict in complex real-time systems.

A considerable body of literature has grown up in the area of Queuing Theory and Markov Processes, but little of this theory leads to usable results for the complex systems encountered in real-world situations. An analytic model which is useful in approximating single-level service systems is the Exponential interarrival time distribution. The service time distribution for the channel is also exponential. If the channel is busy when a service request arrives, the request is put into a queue to wait for its turn on the channel facilities. The maximum queue size, although this would never be the case in practicality, is assumed to be infinite. For this model, queuing theory (see Appendix IV) gives the results: 1) for .5 channel utilization, response time, including waiting time and service time, is 2 times the channel service time; 2) for .75 channel utilization, response time is 4 times the channel service time; and 3) for .9

channel utilization response time is 10 times channel service time.

The results of the analytic model for the Exponential Channel were useful in laying out preliminary systems designs to be tested more accurately with simulation techniques. In the simulation models, inputs arrive with an exponential interarrival time distribution, while service times are a function of the particular device: The CPU service times were assumed to be uniformly distributed about their mean; the channel service times were assumed to be fixed, corresponding to a definite transmission time for the separate cases of drum and disk; service time on the drum was assumed to be uniformly distributed, corresponding to the random rotational delay; service time on the disk was assumed to be fixed for the arm (certainly a simplification) and uniformly distributed for the rotational delay.

The simulation models were designed to provide response times of less than 3 seconds for at least 90% of the inputs to the systems. Average input loads to be handled at peak operating conditions for each system were as follows:

System	Average Input Interval	Drum Accesses/Input	Disk Accesses/Input
5M[1]	50 msec.	4.0	2.5
10M	25 msec.	4.0	2.5

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[1] 5M refers to the system designed to handle 5 million passengers per year.

System	Average Input Interval	Drum Accesses/Input	Disk Accesses/Input
20M	12 msec.	4.0	2.5
40M	6 msec.	4.0	2.5

The 5M system used Model 50 processors with an average service time of 21 msec/input. The other systems used processors with an average service time of 6 msec/input. All systems used the 2820-2301 drum control and storage, with an average service time of 9 msec., and the 2314 disk unit, with an average arm seek time of 75 msec. and an average rotational delay time of 12.5 msec. Results of the simulation runs were as follows:

System	CPU Utilization	Drum Utilization	Disk Utilization	Average Response Time
5M	.38	.68	.69	556 msec.
10M	.21	170	.73	621 msec.
20M	.42	.73	.76	666 msec.
40M	.90	.78	.72	697 msec.

The variance in CPU utilization was due to the limited flexibility permitted in specifying this component. For example, the Model 50 CPU in the 5M system has more than enough capacity, but it could not be replaced by the Model 40. For the 5M through 20M systems, two CPU's were provided, so that a desirable utilization would be around .45.[1] The Model 50, on the other hand, had

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[1] Remember that we are only simulating 1/4 of the overall processor load, i.e. the real-time reservations load

neither sufficient computational power nor I/O power to handle the 10M load. This meant that the next larger processor, the Model 65 had to be specified, with considerable over-capacity. Utilization of the CPU's in the 20M and 40M system was just about right - .42 for the 20M system with two CPU's and .90 for the 40M system with four CPU's.

It would be mentioned that the 10M - 20M - 40M systems form an attractive set from the standpoint of growth considerations. Growth from 10M to 20M would require only the acquisition of facilities for higher I/O rates. From the 20M to the 40M level, the numbers of most component types would simply be doubled for integration into the more powerful system.

The simulation models were programmed and run using a unique technique which deserves comment. The General Purpose Systems Simulator II language was used on the time-sharing facilities at the MIT Computation Center. CPSS II is a high-level simulation language which simplified the task of coding the operation of the system to be simulated for the computer. Since the great majority of effort in simulation is devoted to eliminating errors from the models and in making various changes, the time-sharing mode of operation was extremely convenient. For example, in an afternoon session at the time-sharing console an entire model could be input, debugged, and results obtained using perhaps 10 minutes of computer time. This process would have taken two to three weeks in the regular batch processing mode. Due to the large amount of experimentation and model changes undertaken in this study, complete results that would have taken months to obtain from batch processing were obtained in several weeks of intensive time-sharing operations.

A more subtle advantage of the time-sharing mode is the high level of sustained concentration which it allows. On a one-run-per-day basis, a few minutes of each day would be spent correcting errors and resubmitting for the next run. Results would not be available for examination until at least a day later, when a substantial amount of time would have to be spent in a re-familiarization with the model. This problem does not exist with time-sharing.

In order to determine the input loads given above, statistics on the operation of SABRE were gathered and a simulation model of SABRE was run to confirm their validity.

Individual Designs

The individual systems were designed to meet the requirements laid out in a previous section on preliminary systems design. Three remarks need to be made on the designs in general:

1) core storage for each CPU is specified in an amount considered to be matched to the CPU processing capabilities; 2) all I/O units are attached to the system in such a way that any CPU or channel failure will not prohibit access to the unit be a standby CPU or channel; and, 3) the term "single-record" refers to equipment of the low speed variety such as card readers and punches, and printers.

The 5M system shown in FigureVI-3 utilizes two Model 50 processors with 262K byte memories communicating through shared memories and a direct control feature. Each processor has the maximum configuration of I/O channels: a multiplexor channel to handle low speed devices, and three selector channels for communication with drum, disk, and tape units. The system includes one 2820 drum control, which is the maximum allowed on a Model 50, with two 2301 drum units attached. Two 2314 disk storage units are included, one of which being on-line for the real-time processor, and the other being available as a spare in case of breakdown, is also used by the off-line computer. Both the 2314 and 2820 control units are switchable between the two CPU's. Miscellaneous equipment at the central location includes five tape drives, two card read punchers, two printers, and the duplex console for switching the incoming communications lines between processors. At remote locations there are supplied 500 of the 2260 display units and 100 of the 1977 hard copy terminals. The rental cost of the central equipment exclusive of the duplex

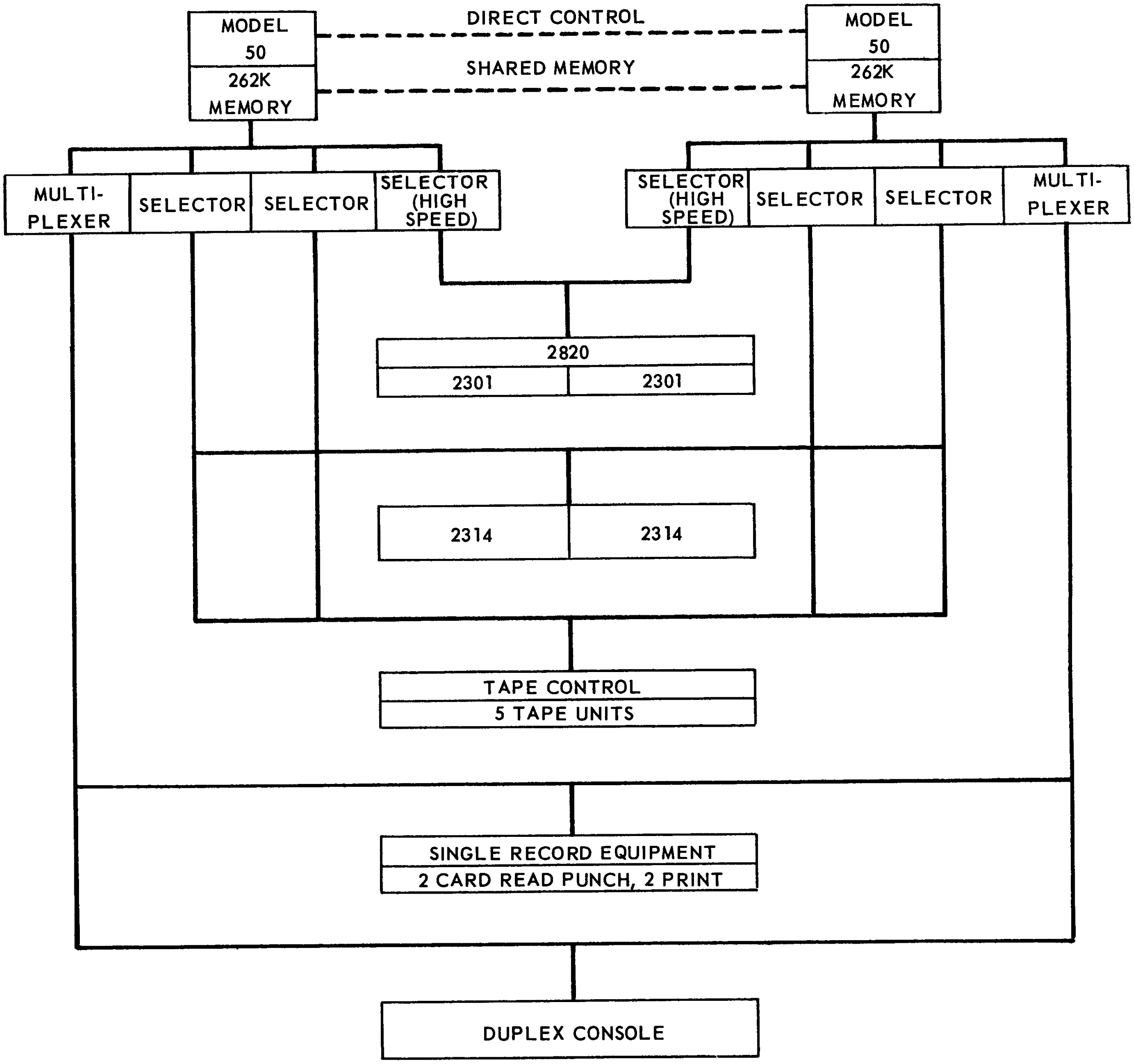

FIGURE VI-5 5M SYSTEM CONFIGURATION

5M System

Quantity	Unit	Rental	Purchase
2	2050H Processor (262K)	$27,500	$1,367,400
2	3274 Direct Control	550	17,200
2	7130 Shared Storage	600	24,200
2	1052 Console	580	27,200
6	6980 Selector Channel	4,200	189,600
2	4580 High Speed Channel	200	8,400
1	2820 Drum Control	2,400	117,160
2	2301 Drum Storage	4,000	192,000
2	2314 Direct Access Storage	10,780	515,900
1	2804 Magnetic Tape Control	930	46,700
5	2401 Tape Units	3,925	189,500
2	2821 Control Unit	1,940	93,000
2	2540 Card Read Punch	1,320	70,000
2	1403 Printer	1,550	68,000
1	Duplex Console	--	RPQ
500	2260 Display Units	--	3,000,000
100	1977 Printer Terminals	--	600,000
		$60,475	$6,526,260

TABLE VI-1 Cost Breakdown on 5M System

console, which would be built on a special contract basis, is $60,475 per month. The purchase price of the entire system exclusive of the duplex console is $6,526,260. The cost breakdown for the 5M system is shown in Table VI-1.

The costs above do not include the communication lines which must be supplied between the central facilities and remote terminals. These costs for all four systems can be estimated from data on leased line costs included in Appendix III.

Software costs are difficult to estimate for the system. IBM would supply many of the required programs. It might be worthwhile, in fact, to contract out to IBM or an independent software firm the task of providing the remaining support.

Personnel salaries for the 5M system should run approximately $8,000,000 a year for machine operations, agents, and supervisors. The possibility of reducing this expense is taken up later in the section on effect of 1980 technology.

The 10M system illustrated in Figure VI-6 uses two Model 65 processors, each with 262K bytes of memory. The two central processors communicate through a special shared memory feature and a direct control facility. Each computer has attached a 2870 multiplexor channel for low speed I/O and four 2860 selector channels for the high performance disk and drum units. A selector subchannel feature on the 2870 multiplexor channel permits the attachment of high-speed tape units as well as the low speed single record and communications equipment. Three 2820 drum controls, each with a 2301 drum attached, are provided. Two of the drums operate on-line with the real-time processor. The other drum is available as a spare in case another drum fails, and as an I/O device for the off-line processor. A similar arrangement is used on the three 2314 disk storage units supplied. Other equipment at the central location includes five tape units, 2 card read punch units, 2 high-speed (1100 line/minute) printers, and the duplex communications console.

Rental cost for the central equipment exclusive of RPQ (special request-price-quotation) features is $104,495 per month. Purchase cost for the entire set of hardware and IBM supplied programs is $8,137,230. The cost breakdown is given in Table VI-2. The number of agent sets, and personnel costs should run roughly the same since the agent sets are determined by geographical locations, and not be the throughput utilization.

A more sophisticated configuration for real-time and time-sharing activity is provided in the 20M system (see Figure VI-7). The Model 67 multi-processor system includes two Model 65 processors with the cynamic relocation feature, four memory banks of 262K bytes storage each, and two channel controls, permitting flexible and powerful I/O facilities. The five 2314 disk units

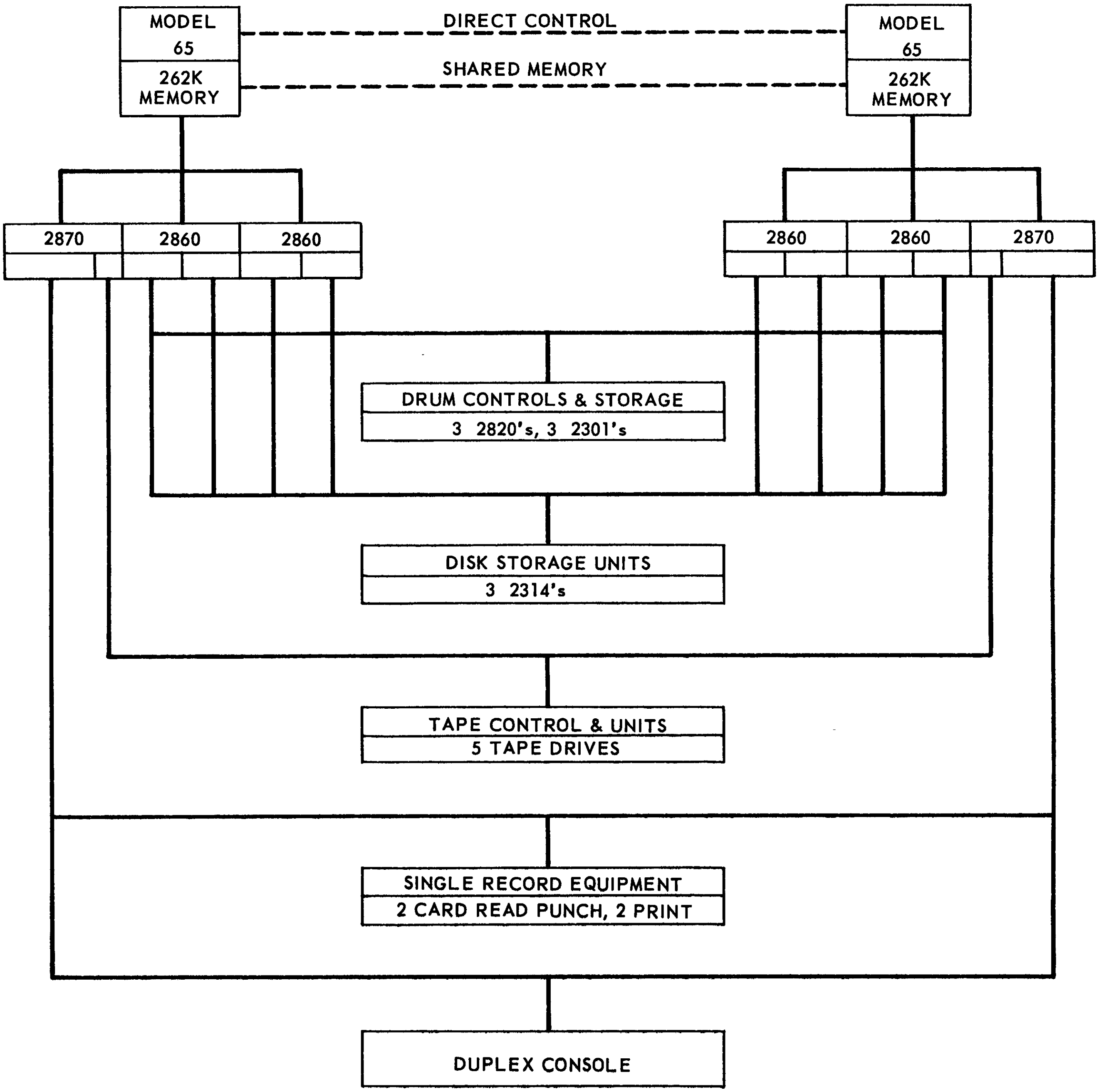

FIGURE VI-6 10M SYSTEM CONFIGURATION

10M System

Quantity	Unit	Rental	Purchase
2	2065A Process (262K)	$45,500	$1,980,000
2	3274 Direct Control	500	18,600
2	Shared Storage	RPQ	RPQ
2	2250 Display Console	1,560	74,300
4	2860-2 Selector Channel	12,000	296,400
2	2870 Attachment	100	4,000
2	2870 Multiplexor Channel	4,400	220,000
2	2990 Selector Subchannel	800	37,000
3	2820 Drum Control	7,200	351,480
3	2301 Drum Storage	6,000	288,000
3	2314 Direct Access Storage	16,170	773,850
1	2804 Tape Control	930	46,700
5	2401 Tape Units	3,925	189,500
2	2821 Control Units	2,090	99,000
2	2540 Card Read Punch	1,320	70,000
2	1403-N1 1100 CPM Printer	2,000	88,400
1	Duplex Console	--	RPQ
500	2260 Display Units/Controls	--	3,000,000
100	1977 Terminal Printers/Controls	--	600,000
		$104,495	$8,137,230

TABLE VI-2 Cost Breakdown on 10M System

and the five 2820-2301 drum control and storage units are attached to the channels in such a way as to make possible full operation if any CPU, memory, channel controller, or channel should fail. A total of ten 2860 selector channels are provided to service the high performance drums and disks. Two independent 2870 multiplexor channels connect to the single record equipment and the duplex communication console. A selector subchannel on each multiplexor channel connects to a total of ten tape units.

At the central location are two card read punch units, four high speed printers, and the duplex console. At remote locations are 700 display terminals and 100 hard copy terminals. Rental cost for the central equipment exclusive of RQP features is $12,888,050. Cost breakdown are given in Table VI-3.

The 40M system shown on FigureVI-8 is at the limits of current real-time technology. A full configuration Model 67 is used, with 4 central processor, 8 banks of memory, and 4 channel controller. Twenty 2860 selector channels and two 2870 multiplexor subchannels are provided, as well as ten 2314 disk storages, ten 2820-2301 drum units, 20 tape drives, 4 card read punch units, 8 high speed printers, and the duplex console. There are 1000 display terminals at remote locations and 200 hard copy terminals.

Rental cost of the central equipment exclusive of RQP features is $300,600 per month. The entire system, exclusive of RPQ's will cost $21,119,100. The cost breakdown for this system is shown in Table VI-4. Personnel for this large system will have salaries totaling $16 million per year.

The cost figures cited for the systems above should be roughly 25 - 50% low in view of the RPQ features, large sized displays, and software costs not included.

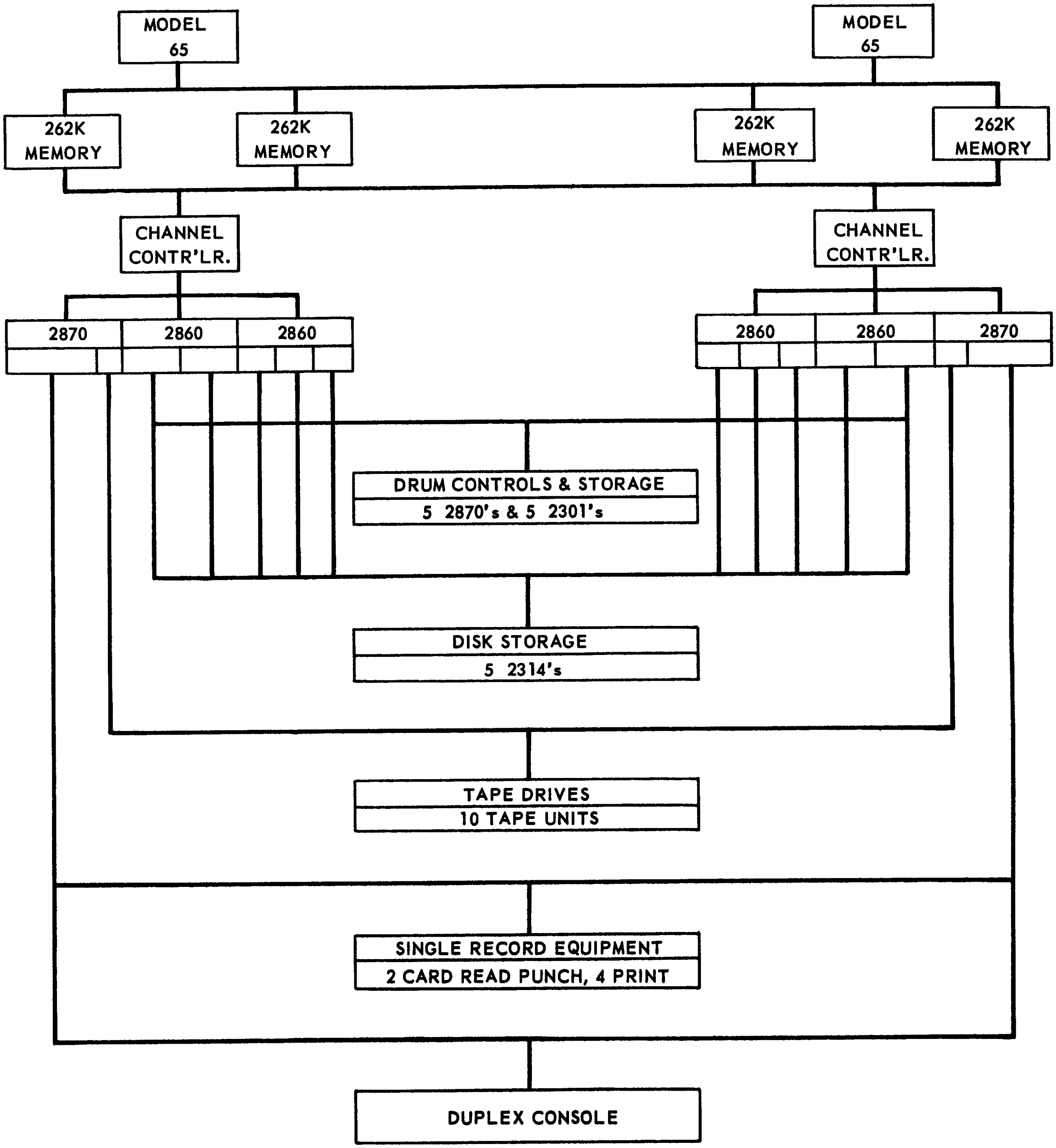

FIGURE VI-7 20M SYSTEM CONFIGURATION

20M System

Quantity	Unit	Rental	Purchase
2	2065 Processor	$ 28,100	$ 1,204,000
2	2067 RPQ (Dynamic Relocation, Shared Memory)	RPQ	RPQ
4	2365 Storage (262K)	37,000	1,640,000
2	2250 Display Console	1,560	74,300
2	Channel Controller	RPQ	RPQ
2	2860-2 Selector Channel	6,000	296,400
2	2860-3 Selector Channel	7,800	385,000
2	2870 Multiplexor Channel	4,400	220,000
2	6990 Selector Subchannel	800	37,000
5	2820 Drum Control	12,000	585,800
5	2301 Drum Storage	10,000	480,000
5	2314 Direct Access Storage	26,950	1,289,750
2	2804 Tape Control	1,860	93,400
10	2401 Tape Units	7,850	379,000
2	2821-3 Control Units	3,290	156,600
2	2540 Card Read Punch	1,320	70,000
4	1403-N1 Printer	4,000	176,800
1	Duplex Console	--	RPQ
700	2260 Display Terminals	--	4,200,000
100	1977 Printer Terminals	--	600,000
		$125,930	$12,888,050

TABLE VI-3 Cost Breakdown on 20M System

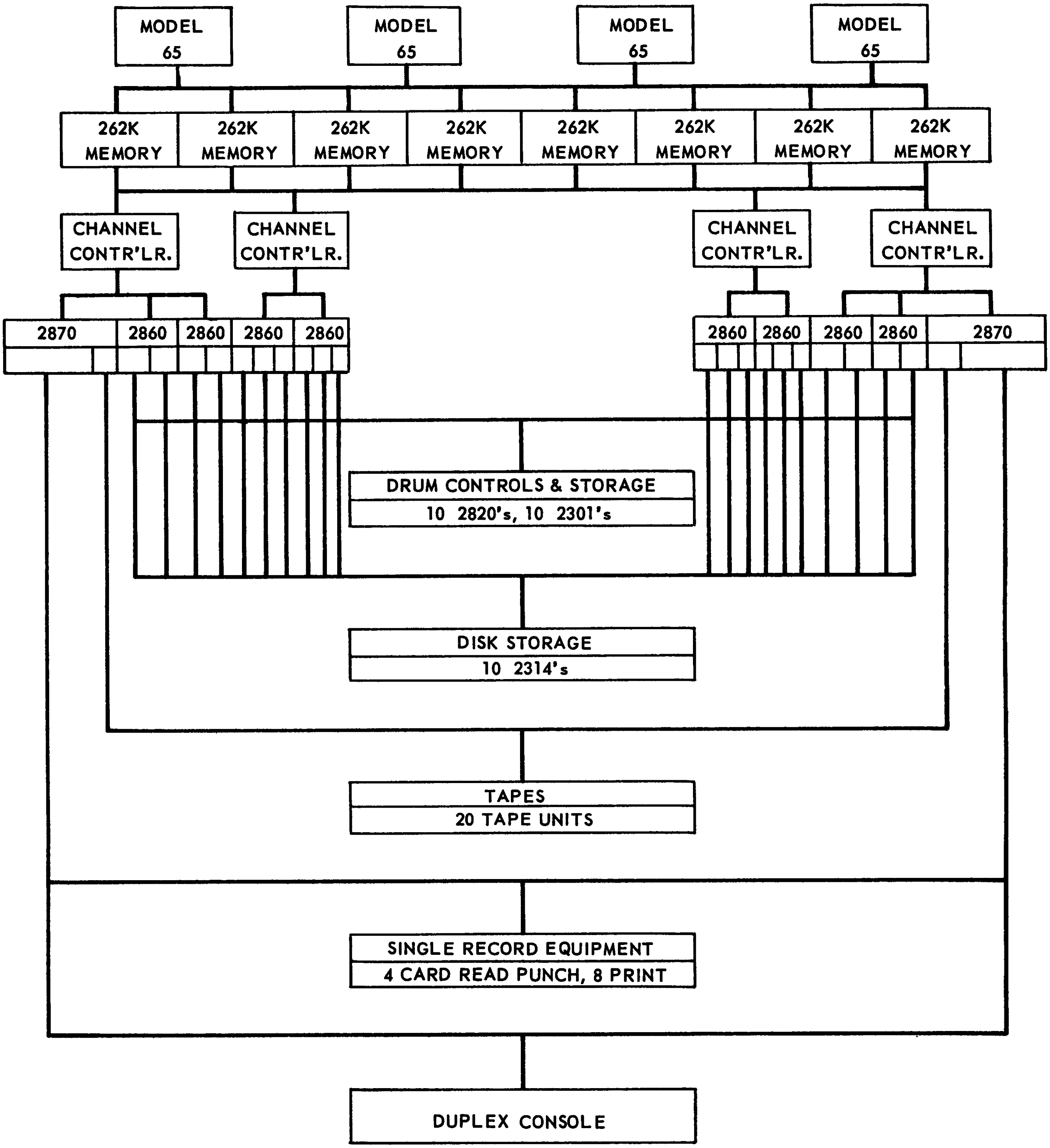

FIGURE VI-8 40M SYSTEM CONFIGURATION

40M System

Quantity	Unit	Rental	Purchase
4	2065J Processor	$ 56,200	$ 2,408,000
4	2067	RPQ	RPQ
8	2065 Memory	74,000	3,280,000
4	Channel Controller	RPQ	RPQ
4	2860-2 Selector Channels	12,000	592,800
4	2860-3 Selector Channels	15,600	770,000
2	2870 Multiplexor Channels	4,400	220,000
2	6990 Selector subchannels	800	37,000
4	2250 Display Console	3,120	148,600
10	2820 Drum Control	24,000	1,171,600
10	2301 Drum Storage	20,000	960,000
10	2314 Direct Access Storage	53,900	2,579,500
4	2804 Tape Control	3,720	186,800
20	2401 Tape Units	15,700	758,000
4	2821-3 Control Units	6,580	313,200
4	2540 Card Read Punch	2,640	140,000
8	1403-N1 Printer	8,000	353,600
1	Duplex Console	--	RPQ
1,000	2260 Display Terminals	--	6,000,000
200	1977 Printer Terminals	--	1,200,000
		$300,660	$21,119,100

TABLE VI-4 Cost Breakdown on 40M System

OPERATING COSTS FOR THE V/STOL AIRBUS MANAGEMENT SYSTEM

To obtain an estimate of the indirect operating costs for the proposed 1980 Airbus System some estimate must be made of the required investment in the computer system and its yearly operating costs. Since the network demand studies have indicated 17 million passengers per year, the 20M system has been selected as appropriate.

The number of agent sets required for the system is determined by the number of stations and positions suitable, and perhaps, by the peak demand for reservations at busy times during the year. In this case, the following number of agent sets have been assumed.

Central Reservations Facility	100
Major Terminals (4 per gate, 8 gates, 13 terminals)	415
Minor Terminals (average of 2, 37 terminals)	74
Management Inputs	50
Spâres, etc.	61
TOTAL Agent Sets Required	700

The 20M system hardware is estimated to cost 12.9 million dollars exclusive of programming software and special features. Assuming that these extras will roughly double the cost, the total computer system investment would be 25 million dollars.

Communications costs are dependent upon the location of the central processor within the transportation network, the network size, and the availability of communication facilities and their expected costs in 1980. As mentioned in Appendix III, arrangements such as Telpac can make a sharp reduction in the communications costs. For purposes of cost estimation, communications costs associated with the reservations, boarding, flight dispatch, and scheduling processes have been estimated at $0.10 per passenger.

The personnel required to operate the system in real-time consist of 100 reservations clerks at the control reservations facility, and about 700 traffic agent personnel in the field whose duties are split between handling reservations and information, and the passenger handling process in the terminal. Computer operating personnel, servicing and repair personnel, and card punch operators, etc. would also be required.

The computer system would require a building which could be the Airbus System headquarters housing all General and Administrative personnel as well as the central reservation facility.

Cost of a Reservation

To determine the cost of providing reservation service within the system, the appropriate portion of the computer systems' costs can be allocated. For personnel, only the cost of the central reservation facility personnel can be considered as caused by reservations. At the airline average of $8,000/year, the 100 reservation agents would receive $800,000/year. For a system handling 16.7 million passengers/year,

$$\text{Salary Costs/passenger} = \frac{800,000}{16.7\text{x}10^6} = \$\ 0.05/\text{passenger}$$

Although the investment in the computer system totals $25 million, the system is used for other functions such as load control, flight dispatch, accounting, etc. as well as maintaining reservations. Similarly, the building required for the central facility and computer is also used as the central headquarters for the system. It is estimated to cost $5 million. If we apportion 1/2 the costs of the computer and building to reservations, and amortize the cost over 20 years at 5% (capital recovery factor = .0802)

$$\text{Amortization Cost per passenger} = \frac{15\text{x}10^6\text{x}.0802}{16.7\text{x}10^6} = \$.075/\text{passenger}$$

Assuming $0.10 per passenger for communications costs is incurred for a reservation made in advance of boarding, the total cost of making a reservation is $0.225 per passenger. If one quarter of the passengers desire reservations, the extra cost of maintaining the reservations facility could be recovered by having a surcharge of $1.00 for a reservation. By this means, the system during busy peak periods would operate as a reservations system giving advance information of the size of the peak loadings for scheduling purposes, eliminating passenger crowds in the terminal waiting in line for various flights, and raising the ticket price during busy periods to encourage off-peak travel. At the same time, it would allow the freedom of no-reservations service on a standby basis during regular, normal service for the briefcase, shuttle passenger.

EFFECTS OF 1980 TECHNOLOGY

There can be no doubt that today's most recent computer designs will appear as archaic in 1980 as 1950 computers (Univac I, IBM 701) appear now. Projecting technology by 15 years in what is probably the most dynamically changing field of technology is, of course, nothing but sheer speculation. However, it may serve a useful purpose to make educated guesses, particularly in terms of performance and cost, on the effects that the vast technological advances to take place by 1980 will have on the real-time computer system for the VTOL network.

Computers historically have tended to evolve by generations. In the early 1950's computers used tube circuits for logic and various devices such as electrostatic storages (IBM 701) and accoustic delay lines (Univac I) for memory. In the mid-1950's, the core storage became practical and fairly high speeds were achieved by processors using vacuum tubes and core memories such as the IBM 704 and 709. In 1959 the first solid state computers were introduced, replacing tubes with transistors. At the same time memory cycle speeds were increased so that the transistorized IBM 7090 could achieve 5 times the speed of the 709.

In this sequence of development, vacuum tube computers were called "first generation" and solid state computers "second generation." At the present time, the first so-called "third generation" computers are beginning to be delivered, utilizing micro-miniaturized logic circuits.

These generations of computers have tended for economic reasons to last at least five year. This is due to the necessity of the computer manufacturer's making money on their machines before they are replaced with more advanced models.

We can fairly safely predict the arrival of "fourth generation" hardware. It will be characterized by batch fabricated logic circuits and memories. In this generation, entire sections of computer logic and entire modules of memory will be manufactured as one "throw away" unit. Should an individual component in the module fail, the entire module would be replaced. Batch fabrication promises to lower cost of both central processor and memory units by significant amounts. It also appears probable that processing speeds can be increased with this mode of construction.

The "fourth generation" hardware can be expected to arrive in the early 1970's. Prices of processing units, memory, and I/O channels should be a fraction of their counterparts in the small, medium, and large scale third generation series. Large processors in the fourth generation hardware should be capable of executing 20 million instructions/second and storing a million words in memory for a rental price, excluding I/O devices, in the vicinity of $50,000 a month. A medium sized processor, processing 5 million instructions/second and storing 100,000 words in memory, should rent for around $20,000 a month. A small scale computer, capable of executing 500,000 instructions/second and storing 10,000 words in memory would cost $4,000 a month.

With central processors becoming smaller, cheaper, and faster, major effort in the 1970-1980 decade will go into improving input/output hardware facilities and improving, through software, the man-machine interface. Major breakthroughs can be expected in the area of random access storage facilites. A possibility here is the cryogenic storage unit, using the superconductive properties of certain metals to store information. Research in this area indicates that mass memories consisting of billions of bits may be feasible. The cryogenic store may also have the facility of associative addressing, where rather than addressing a specific location to read out the contents, the contents themselves are addressed. Cryogenic associative memories may make possible a file search in microseconds which would take several minutes on present day machines.

Certain types of I/O equipment should remain with us for a long period of time. Small improvements in performance, along with minimal price cuts can be expected for such devices as tape drives, punched card equipment, and printers. Remote terminal devices, such as typewriters and CRT displays, are presently rather high priced. As time-sharing operations become more common, prices of remote terminals should drop, particularly from the competition offered by independent specialist manufacturers.

The uses of computers in another 15 years are going to be so broad that ways must be found for improving man-machine communications without the necessity for costly special purpose I/O equipment. With this device, a housewife could place an order to a computerized supermarket, a businessman could place a stop-loss order on a certain stock, or a traveler could make reservations for our VTOL transportation system. Audio response devices already exist which can assemble the output messages required for such a mode of operation. However, much development is necessary before this mode would be economically attractive for a large number of communications lines coming into the system. The cost saving this mode would offer, depending on the cost of the I/O equipment necessary, can be seen from the large proportion of operating personnel costs involved in the 5, 10, 20, and 40 million passenger/year designs presented earlier.

CONCLUSIONS

It has been shown that a truly integrated management information system will be economically feasible for a 1980 VTOL transportation network. Newly announced third generation computer hardware and software makes this type of system possible, and fourth generation hardware, available in the early 1970's will further decrease the cost for such systems.

It is expected that all airlines, and most transportation systems will have these systems in the future because of their capability to increase the system's efficiency of operation (such as vehicle utilization, higher load factors, better data for scheduling, etc.), and also to increase the productivity of the system ground personnel. A new transportation system starting with such a computer system has an unparalleled opportunity to develop efficient management methods and lower transportation costs.

The cost of providing a reservation using the computer system is only $0.225 compared to present estimated level of $3.50, and even this cost can be offset by marketing the reservation service as an option to the passenger.

The benefits provided by the integrated management information system can be summarized as follows:

1) Facilities for advanced reservations for passenger and freight;
2) facilities for handling passengers and freight with no advance reservations in an optimal fashion, based on a "first-come first-served" priority scheme;
3) integration of advance reservation and standby information with the dispatching and scheduling operation on a continuous basis;
4) high powered computational facilities for optimizing route structure, schedules, and assignment of vehicles and crews;
5) data processing facilities minimizing the personnel necessary for accounting, marketing, and administration, but maximizing the need for high caliber personnel for the more demanding functions of management and planning; and,
6) information retrieval, display, and simulation facilities for the specific purpose of aiding management in decision making.

Areas for continuing reserach turned up in this preliminary study are endless: traffic flow analysis, crew scheduling, vehicle scheduling, customer preference in scheduling and reservations, man-machine communication, real-time system characteristics, to name a few. In the next several years, operational experience will begin accumulating on the new systems which have been described in this study: Project MAC, United Airlines, and others. Design for the management information will be continuous, starting with the most preliminary stages, and continuing through system implementation and operating experience. As in the case of the SABRE system, much detailed information about system behavior will become available only after installation.

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APPENDIX I NETWORK STATISTICS - VSTOL AIRBUS SYSTEM - 1980

Terminal	Originating Passengers/ Day	Take-offs/ Day	Terminal	Originating Passengers/ Day	Take-offs/ Day
DCA	1,550	38	HVN	410	31
DUL	1,070	17	WBY	310	5
BAL	940	18	GON	290	10
BOS	2,030	69	HFD	760	54
BOC	2,060	79	ACY	240	5
MAN	170	4	BMR	2,120	59
WOR	500	25	WAS	2,250	69
NBD	210	17	MIT	1,250	93
PVD	1,200	45	TBO	760	17
WIL	660	14	NYC	1,250	61
PHL	2,140	48	ORF	1,430	31
TRE	290	6	RIC	880	24
REA	320	69	PPA	2,990	147
LAN	420	36	PHF	820	19
ALL	580	73	YRK	370	8
HAR	580	12	AVP	210	5
WBA	320	7	SGC	630	44
SPR	750	45	NWK	160	33
PIT	120	4	ISP	350	37
BPL	210	22	EQM	310	27
JFK	2,220	81	EHM	130	18
LGA	2,970	147	PWM	200	5
JRB	850	70	FIT	80	3
EWR	1,490	113	BTN	300	8
BDR	460	22	LAW	260	21
			Total	48,810	1,915

APPENDIX II. STATE-OF-THE-ART 1965

II-1 Compatable Computer Families

Model	Standard* Rental	Range in Rental	Add Time (msecs)	Cycle Time Per Bits (msecs.)
System/360 (IBM)				
Model 40	$19,000	$ 5-35,000	11.9	2.5 /16
Model 50	27,000	14-55,000	4.0	2.0 /32
Model 65	38,000	25-90,000	1.3	.75/64
Model 75	47,000	54-170,000	.8	.75/64
Spectra 70 (RCA)				
Model 45	$19,000	$ 8-30,000	9.6	1.44/16
Model 55	27,000	14-60,000	2.6	.84/32
Series 200 (Honeywell)				
1200	$19,000	---	3.3	1.5 /6
2200	22,000	$5-30,000	?	1.0 /6
4200	30,000	---	7.5	.75/24
600 Series (G.E.)				
625	$47,000	$40-100,000	3.0	2.0 /72
635	52,000	44-105,000	1.8	1.0 /72
300 Series (CDC)				
3400	$26,000	$13-36,000	3.0	1.5 /58
3600	40,000	40-75,000	7.0	1.5 /48
3800	43,000	45-80,000	.8	.8 /48
6000 Series (CDC)				
6400	$31,000	$25-95,000	1.1	1.0 /64
6600	55,000	60-130,000	.3	1.0 /64

*2 I/O channels, 10 tapes, printer, card reader/punch, core size appropriate to compute power.

II-2

RANDOM ACCESS STORAGE

Model	Type	Capacity	Access Time	Cost/Month
IBM 7320	Drum	830K bytes	8.6 msec.	$2,300
RCA 70/565	Drum	1M bytes	8.6 msec.	2,100
CDC 862	Drum	2.1M char.	8.6 msec.	1,740
Hon. 270-1	Drum	2.6M char.	27.5 msec.	925
IBM 2301	Drum	4M bytes	8.6 msec.	2,000
CDC 861	Drum	4.2M char.	17 msec.	1,850
Hon. 270-2	Drum	5.2M char.	27.5 msec.	1,565
DEC 237	Drum	6M char.	16.6 msec.	1,850
GE MD-20	Drum	6M char.	8.5 msec.	2,300
Hon. 270-3	Drum	7.8M char.	27.5 msec.	2,205
CDC 828	Disk	33M char.	187 msec.	2,400
CDC 838	Disk	66M char.	187 msec.	3,600
CDC 6603	Disk	75M char.	267 msec.	5,600
IBM 2302-1	Disk	112M bytes	165 msec.	5,600
GE MD-200	Disk	200M char.	---	7,000
IBM 2314	Disk	207M bytes	75 msec.	5,250
IBM 2303-3	Disk	224M bytes	165 msec.	7,900
IBM 2321	Data Cell	400M bytes	400 msec.	2,300
RCA 70/568	Data Cell	500M bytes	300 msec.	2,700

APPENDIX III COMMUNICATIONS COST

There are two types of digital communications service offered in the Bell System at the present time:

WATS (Wide-Area-Telephone-Service): This permits unlimited calls over a specified area on the regular telephone network. This service, as an example, costs $2,275/month for a phone in California with unlimited calls throughout the U.S.

TELPAC: This service is a special priced rental for private communications suppled by Bell. There are four types, ranging from TELPAC A--which allows transmission of up to 5,000 char./second for $15/mile/month,--to TELPAC D--which allows transmission of up to 100,000 char./second for $45/mile/month.

At each end of the communications line there must be a "Data Phone" costing from $30 to $75/month depending on the speed of transmission.

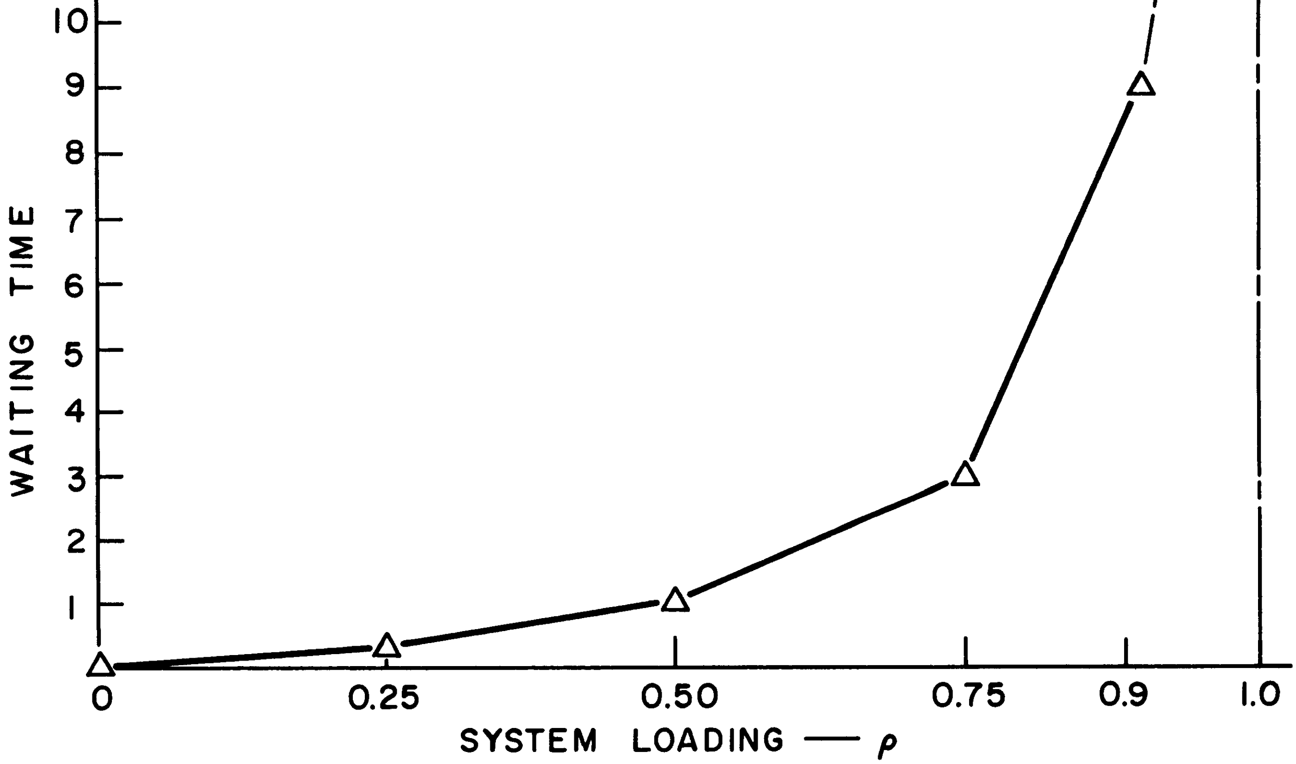

FIG. VI - 9 AVERAGE DELAY BUILDING WITH UTILIZATION

APPENDIX IV. THE EXPONENTIAL CHANNEL

Let Ts = average service time

Ta = average interarrival time

$$p = \frac{Ts}{Ta}$$

Wg = average steady state waiting time

For exponential interrival and service time distributions,

$$Wg^{*} = \frac{p\ Ts}{1-p}$$

a plot of Wg as a function of p, with Ts set equal to 1 is given in Figure VI-9.

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*See Morse, Queues, Inventories, and Maintenance, pp. 14-22.

PART VII

INDIRECT OPERATING COSTS

VII

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INTRODUCTION

In airline and aircraft engineering terms, direct operating costs are those directly associated with the aircraft operation and design. Indirect costs are the remainder of the operating costs of the airline, some of which are directly associated with the production of transportation (i.e. the station operations), and some of which are overhead costs (general and administrative, etc.).

The indirect costs are mainly salaries and wages for ground employees, and are therefore determined by labor agreements, labor classifications, and wage rates. They are affected, however, by technical factors such as design of the terminal and its equipment, and the computer system for accounting, data handling, etc. in the management process. While the direct costs are used by engineers to select and design a vehicle for short haul purposes, a study of the indirect costs will be necessary to design the ground terminals and determine the ground operations and the methods of management to ensure a low cost short haul air transportation system.

Indirect costs tend to be independent of the length of haul, i.e.,a fixed terminal cost or an overhead cost to be spread over the total transportation production. The level of overhead costs (like general and administrative expense, advertising, etc.)

are very dependent upon the size of the system, or the size of the production in terms of revenue passenger miles (RPM). The RPM total is the product of the number of passengers handled times their average trip length. A short haul system has a low average passenger trip length, and therefore must handle more passengers to attain the large production of RPM required to lower the level of these overhead costs.

But the fixed terminal costs vary directly as the number of passengers handled and it becomes essential to the success of a large size, short haul system that the terminal costs be kept very low. A large proportion of them are incurred in the station operations where the loading and unloading, and trip preparation occurs. These terminal costs become much more important to any form of short haul transportation where they often completely dominate the costs which vary with distance. Therefore, the basic problem of short haul transportation is how to eliminate, reduce, or minimize these terminal costs.

In the airline business, there is a high level of station operations, and station service for the passenger. The indirect costs are much higher for the international long haul carriers, and gradually lower levels of service and costs appear as the domestic trunk airlines, local service carriers and helicopter airlines are examined. For intercity bus carriers, the equivalent of airline indirect costs are an order of magnitude smaller.

For commuter transport (such as subway, bus, rail, etc) where fixed terminal costs or passenger service expenses cannot be tolerated, self service methods, monthly ticketing, a complete lack of terminal buildings, station personnel and equipment are often seen.

The level of these distance-independent terminal costs are of particular interest in the specification of fares for a short haul VTOL system. The level of costs incurred in terms of dollars per passenger handled, or dollars per vehicle departure, can be critical to the successful competition of an air system with a fast ground system. It is fair, however, to point out that these costs are only indirectly associated with the type of vehicle used. The passenger handling costs for example, of an air and ground system should be similar at the same levels of ground service, and this point should be kept in mind in comparing ground and air transport systems.

CLASSIFICATION OF AIRLINE INDIRECT COSTS

Some explanation of the classification used in this report is given by the following description of the various operating functions. These functions are necessary to the operation of any passenger transportation system. They can be fulfilled in various ways, and with various levels of service or effort, but they remain basic or essential to the system operation.

Passenger Service

This function covers activities related to passenger comfort, convenience, and safety, during the flight such as cabin crew costs, food and entertainment expenses, and related support expenses, such as training, supervision and passenger liability insurance. With the exception of food, these expenses may be allocated over the duration of the trip using revenue passenger miles as a suitable parameter.

Aircraft Servicing

This function covers all expenses caused by the ground handling of arrival and departure vehicles such as inspection, servicing and fueling, routine checking, etc., and aircraft control (communications, meteorology, flight planning, schedule control, etc.). These costs are incurred because of the beginning and ending of the trip and are almost independent of length of haul. The costs incurred are proportional to the number of departures although the difference between an originating departure and a transit stop departure must be appreciated.

Traffic Servicing

This function encompasses all activities related to processing passengers, baggage and cargo payloads at the terminals such as ticketing, boarding, baggage weighing and handling, information on departure times and gates, cargo loading, etc. The costs are incurred mainly by the passenger loading process, and are totally independent of length of haul. The costs incurred are proportional to the number of passengers handled, and are very much affected by the typical passenger, the level of service offered and the volume of business through the terminal.

Servicing Administration

The activities of Aircraft and Traffic Servicing form essential field or station operations of the air transport system, and are direct transportation expenses. To support the field personnel some supervision, accounting and payroll, and general administration expenses must be incurred at each station. Aircraft and Traffic Servicing costs and the Administration expense constitutes "Station Operating Costs" referred to later in this section.

Reservations and Sales

This general system function is related to selling space to passengers and cargo. For efficiency in selling space, to ensure high load factors and good scheduling of services, the airlines have maintained a reservations approach to space control from their beginning. The costs are incurred in maintaining various field sales offices, and centralized telephone reservation and information services, in operating and maintaining a computer reservations system and its communications, in preparing and distributing tariffs and operating schedules, and paying ticket commissions to external travel agents. The costs are independent of length of haul, and vary directly as the number of passengers originated.

Advertising and Publicity

This covers all promotional costs throughout the system and is usually correlated to expected revenues through a budget. It may be expressed therefore as a percentage of revenues, or revenue passenger miles.

General and Administrative

These expenses encompass all items of a corporate, or office nature such as accounting, purchasing, legal, payroll, and various management functions. They may be expressed as a percentage of revenues, or revenue passenger miles.

Ground Facilities

The expense of maintaining ground buildings such as offices, terminals, hangars, etc., and ground vehicles such as trucks, ground servicing vehicles, etc., can be allocated to depreciation or rental costs and to building maintenance. It can be further allocated to local or field expenses (e.g. terminals, hangars, ground servicing vehicles), and general system expenses (overhaul base, headquarters, etc.). The former can be allocated on a basis of number of departures and the latter as a percentage of revenues, or revenue passenger miles.

Landing Fees

Since airports are normally maintained by some local authority, the airlines normally pay a fee based on nominal landing weight, number of passengers, or a tax based upon amount of fuel purchased, etc. These costs are directly proportional to the number of aircraft departures, and the function is associated with the termination of the trip and not its length.

Since we are dealing with short haul transportation by air it is pertinent to examine the evidence of indirect costs for the present airline systems, particularly the local service and helicopter airline systems whose service is similar to that proposed for the V/STOL system in the Northeast Corridor. As well, the indirect costs of U.S. Class I Intercity bus carriers are shown on a comparative basis in order to show that very low costs can be obtained, and to examine the possibility of applying such methods to an "airbus" system. Finally, an estimate total of the VTOL and STOL Airbus Systems costs are made in order to estimate total costs and suitable fares.

ANALYSIS OF INDIRECT COSTS

Number of Employees and Their Productivity

Since the majority of indirect costs are ground personnel salaries, it is of interest to examine the numbers and distribution of employees for the airlines and intercity motor carriers. Table VII-1 shows the number of employees of the airline and motor bus carriers since 1949, and their productivity in terms of revenue passenger miles per employee. The airline results show a steadily increasing productivity for the airline ground employee as the business has grown, but at a level much lower than the productivity of the bus employee even when drivers are counted. The bus drivers perform various duties such as ticketing, information, baggage handling, etc., and are included for this reason. This dual role for transportation employees is a powerful method of increasing efficiency and productivity where it is accepted practice and unopposed by labor unions. The use of drivers to perform ground duties at bus stops along the line between terminals, and the practice of leasing transportation facilities and agents at restaurants, motels, hotels, etc. keeps the bus carriers' employment low while incurring extra "purchased" transportation expenses.

Table VII-2 shows the distribution of employees for the airlines, bus carriers and Los Angeles Helicopter Airways. While

Employee Productivity of U.S. Airlines and Bus Carriers

	Domestic U.S. Airlines (Ref.VII-2)					Intercity Bus Carriers, Class I (Ref.VII-4)			
Year	RPM (10^{-9})	Ground Employees	$\frac{\text{RPM}}{\text{G.E.}}$ (10^{-3})	Air Employees	$\frac{\text{RPM}}{\text{Total Emp.}}$ (10^{-3})	RPM (10^{-9})	Other than Drivers	Drivers	$\frac{\text{RPM}}{\text{Total Emp.}}$ (10^{-3})
1949	8.6	68,208	126	12,786	106	19.0	26,570	21,654	394
1950	10.1	69,561	145	13,225	122	17.0	25,970	20,450	366
1951	12.9	80,376	154	15,377	135	18.1	23,091	19,435	426
1952	14.2	87,591	162	16,481	136	17.3	22,386	18,973	419
1953	17.4	91,703	190	17,689	159	16.6	22,245	19,101	398
1954	19.6	91,158	215	18,383	179	14.8	20,498	17,968	385
1955	22.7	101,130	225	21,073	186	14.6	19,524	17,199	398
1956	25.5	108,633	235	22,867	194	14.6	19,292	17,289	400
1957	28.1	120,657	233	26,533	191	14.5	19,735	17,200	393
1958	28.5	120,775	235	26,375	194	13.7	18,346	16,173	398
1959	32.6	134,722	242	29,448	199	13.5	17,623	16,369	398
1960	34.0	139,985	246	27,946	205	13.3	17,931	17,104	380
1961	34.6	139985	247	29,956	205	13.9	18,221	17,181	393
1962	37.5	142,678	263	30,149	218	15.1	18,324	17,953	417
1963	42.7	145,192	294	31,031	242	15.3	18,263	18,120	421

TABLE VII-1

Employee Distributions of U.S. Airlines, LAA Helicopter, Buses

1962

	Airlines	LAA	Buses
1) Pilots, Co-pilots, or Drivers	8.0%	12.4%	50.0%
2) Supervisors, others	2.4	1.5	4.4
3) Pursers, Stewardesses	7.0	10.0	--
TOTAL AIR	17.4	23.4	54.4
4) Communications	2.0	3.0	--
5) Mechanics	20.0	17.0	12.0
6) ATS, Station employees	27.0	22.4	23.0
7) Office employees, G & A	21.0	23.8	9.0
8) All others (Supervisory, insurance)	12.0	9.6	3.0
TOTAL GROUND	82.0	75.8	47.0
Number of Employees	171,288	197	35,717
Number of Vehicles	1,837	5	11,632
Ratio of Pilots to Vehicles	7.25	4.8	1.51
Ratio of Mechanics to Vehicles	18.6	6.8	0.365

TABLE VII-2

the short haul helicopter carrier distribution closely resembles the airline distribution, the bus carriers have a preponderance of driver personnel, and no personnel at all in the passenger service, and communications categories. Passenger service costs are incurred in air transportation by legal requirements (FAR Part 121 and Part 127) for cabin attendants on a seating capacity basis. The cabin crew are deemed necessary to operate various escape hatches, doors and emergency equipment, and direct passengers to a safe evacuation in the event of an accident or incident with its incipient dangers of fire. The communications personnel are associated with the flight dispatch, flight planning and meteorology, aircraft loading and weight planning, etc. which are normally considered necessary for flight vehicle operations.

Employee productivity can be indicated for the various airlines by plotting revenue passengers per employee, and revenue passenger miles per employee ratios versus the average passenger trip length. Figure VII-1 shows the former, which indicates that the local service carriers and helicopter carriers are handling more passengers per employee than the longer haul carriers and a definite trend is visible. The bus carriers, however, are almost an order of magnitude better in this measure with 4,800 passengers per employee at an average trip distance of 85 miles for 1961.

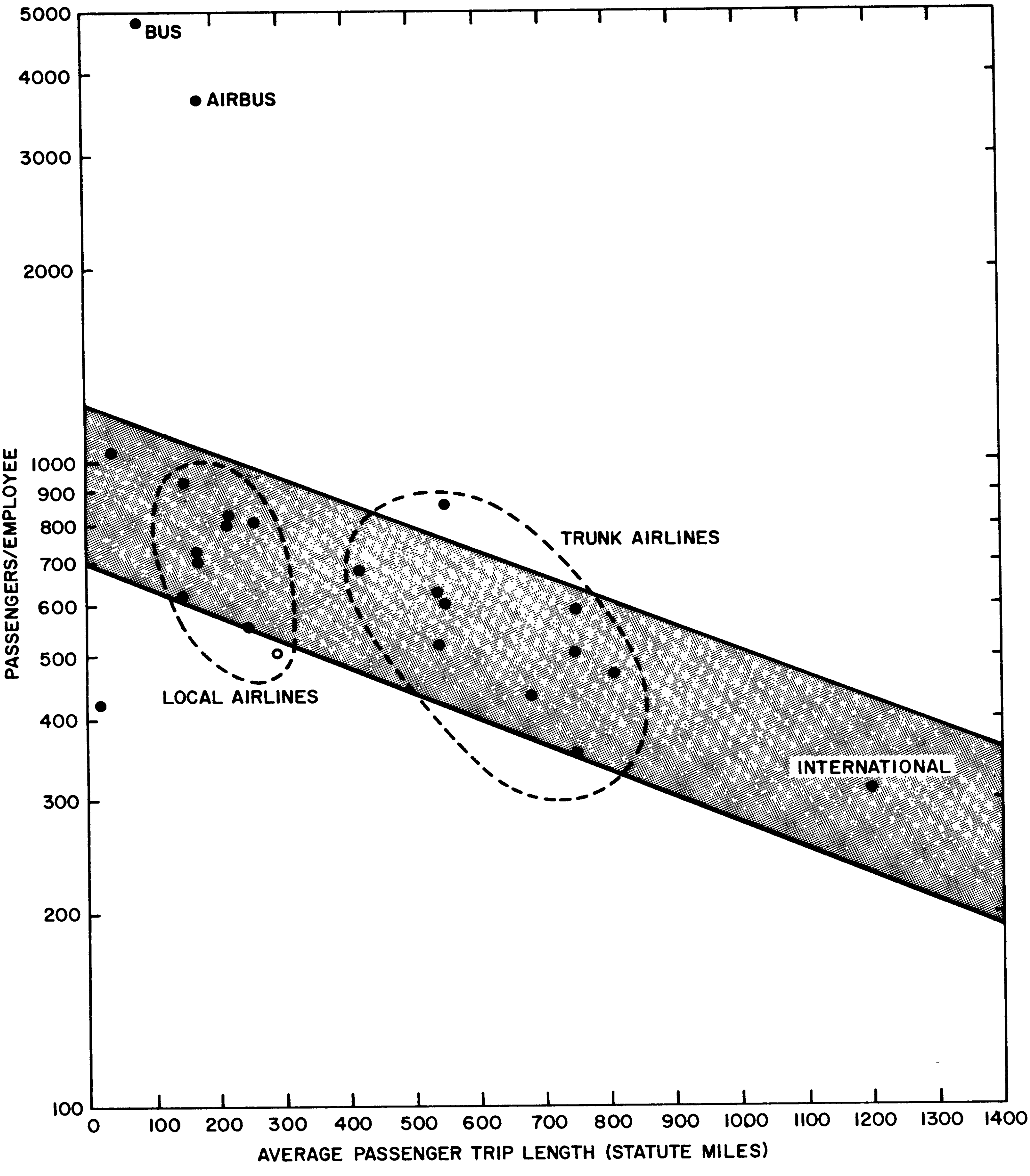

Figure VII-1. PASSENGER/EMPLOYEE RATIO, U.S. AIRLINES-1964

The situation is reversed, however, when the latter measure (RPM/employee) is examined, (Figure VII-2). The longer average passenger trip length more than compensates for the long haul carriers' lower values of passengers per employee. Here, the bus carriers and major trunks have similar values. The local service carriers' values are roughly one-half the trunks, and the helicopter carriers are less than one-quarter as productive by this measure. Revenue is generally proportional to revenue passenger miles, and indirect costs are mostly employee salaries, so that the short haul air carriers have a much higher indirect cost per revenue ratio due to the powerful effect of average passenger trip length in generating revenue.

Station Operational Costs

If station operational costs (Aircraft and Traffic Servicing plus Station Administration) are expressed as dollars per passenger, it is seen in Figure VII-3 that they tend to increase with average passenger trip length. The locals and domestic trunks have costs varying between four and seven dollars per passenger with the large domestics and international carriers having costs ranging up to nineteen dollars per passenger. The helicopter carriers have costs of the order of three dollars per passenger while the 1962 bus carrier results are 0.70 dollars per passenger.

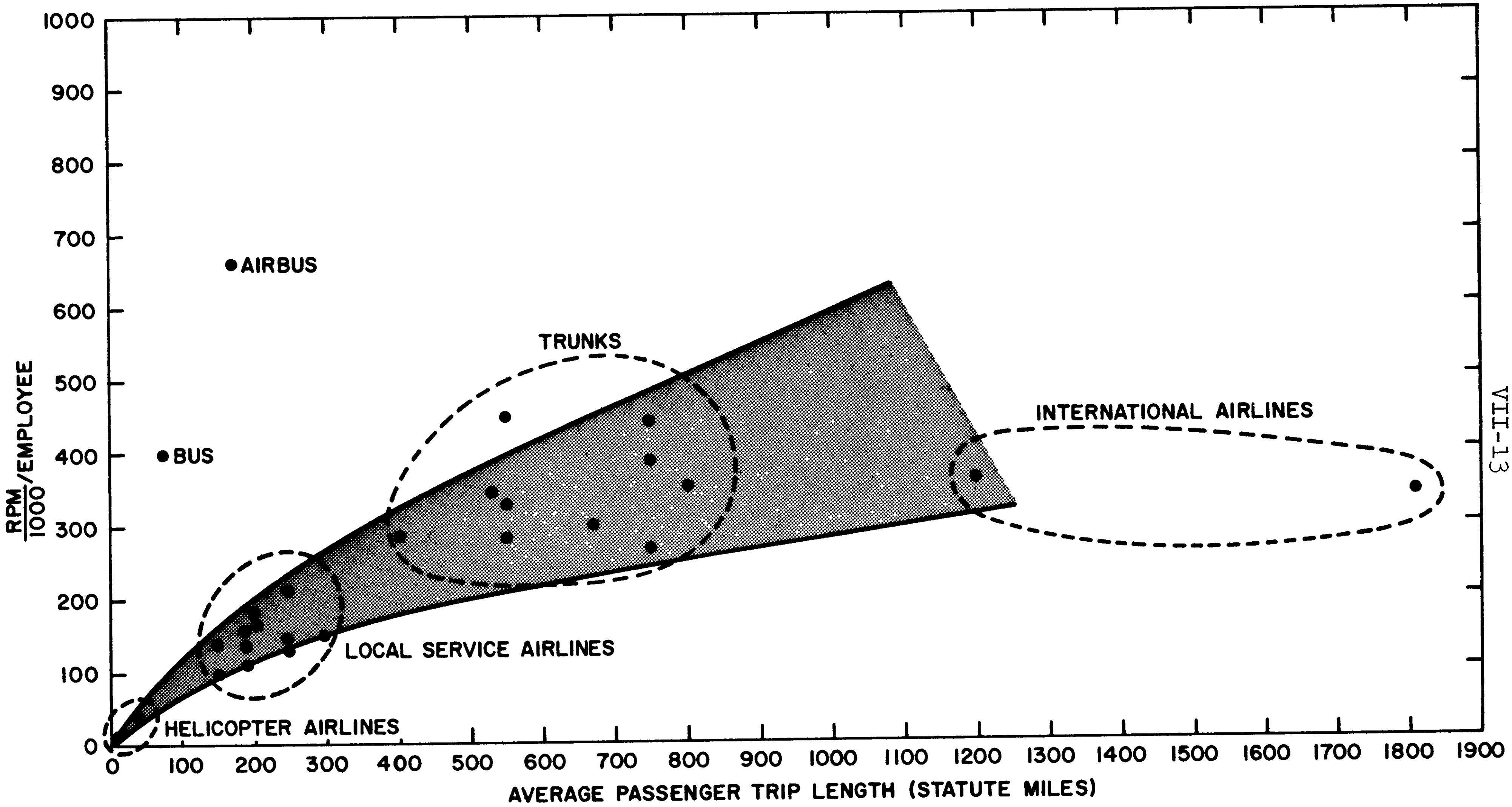

Figure VII-2. REVENUE PASSENGER MILES/EMPLOYEE, U.S. AIRLINES-1964

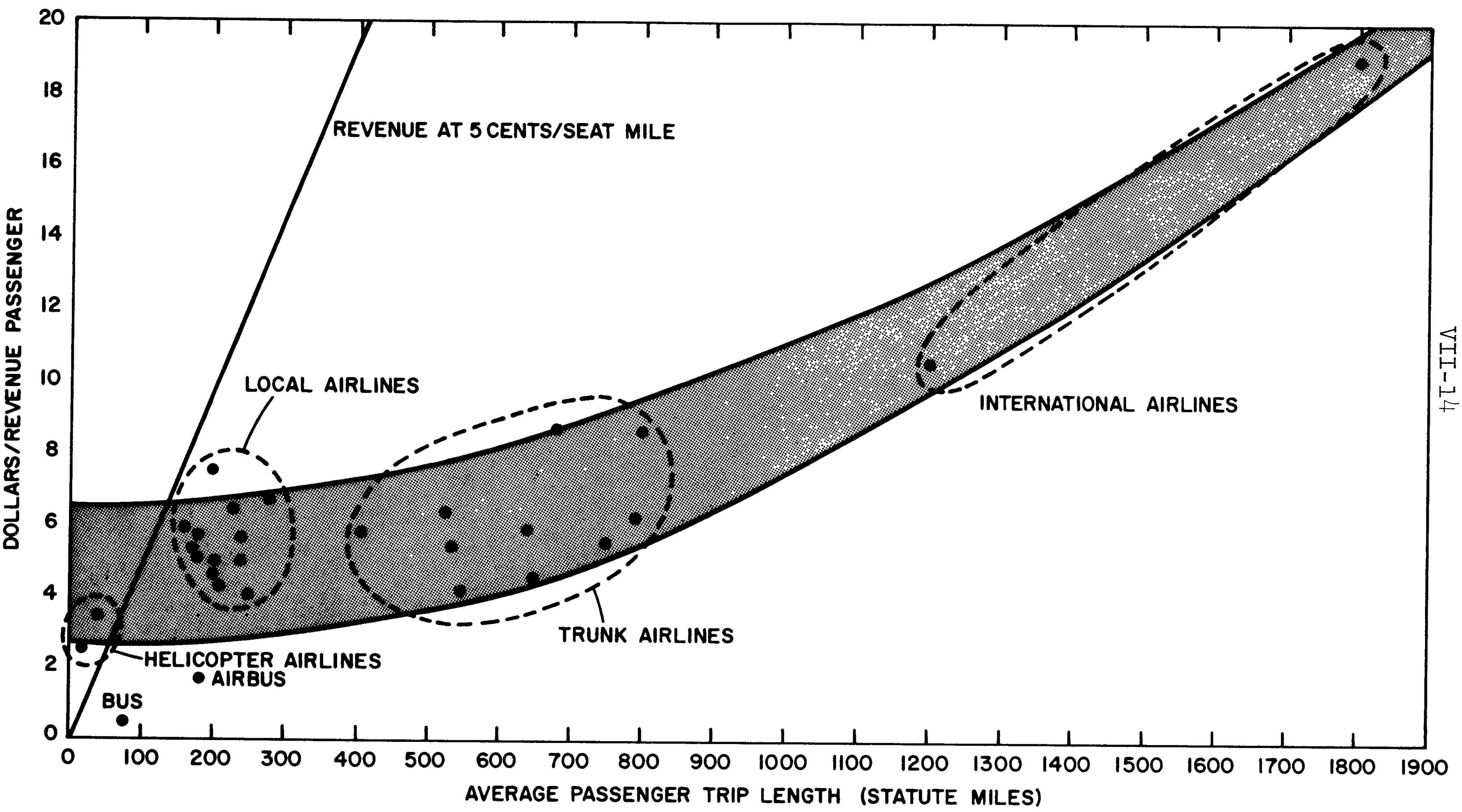

Figure VII-3. STATION OPERATIONS COST PER REVENUE PASSENGER-1964

The importance of low station operation costs is indicated by the revenue line generated at five cents a seat mile. The helicopter carriers would not even recover station operation costs at this revenue rate although their station costs are roughly one-half the normal airline cost. The local service carriers are very close to the line at their average passenger trip of the order of 250 miles, while the domestic trunks and international carriers are well below the line due to their much longer passenger haul.

The bus carriers with an average passenger trip of 85 miles are also well below this revenue line. It is important to recognize the difference between a bus stop and a bus terminal. The ability of a motorbus to stop for the discharge and pick up of passengers at various restaurants, hotels, gas stations at various points along the line has been well exploited. Here, no investment in ground facilities or personnel exists, with the local proprietor supplying shelter and information, and the bus driver supplying the necessary ticketing and baggage handling when the bus arrives. A similar operation exists in helicopter operations (both for scheduled and air taxi operators) where there is a basic difference between helistop and heliport ground operations. This type of line haul, multi-stop operation would seem to be essential to successful short haul transportation. VTOL aircraft can perform multi-stop segments without incurring long stopping times or requiring major facilities. It is not feasible for fixed wing and STOL aircraft because of the time spent in air and ground maneuvering, and the necessity of a runway. Thus, an AIRBUS system would require VTOL vehicles.

The economics of scale do not seem to affect station operations costs as indicated by Figures VII-4 and VII-5. There is a very poor correlation in Figure VII-4 between station operations costs and station loading (average passengers per day per station). The large airlines have high station loadings,(and high average loads per departure) and yet incur higher costs per revenue passenger, probably due to their larger terminal buildings and higher level of service. The helicopter carriers have low station loadings but lower costs due to smaller stations and simpler ground service. Discussions with airline ground operation engineering personnel have indicated that the increasing complexity of a major passenger terminal tends to offset economies of scale and require increasing personnel and equipment to perform the loading process in roughly the same time interval. It is also stated that with proper consideration given to the design of the terminal and its equipment (along with the vehicle design), the economies of scale can be achieved at major terminals.

Similarly, in Figure VII-5 plotting station operations cost per passenger versus average passenger loads per departure does not show significant correlation, except for the local service carriers. In this case all the carriers are still using walk-on ramp loading from a simple terminal building, and the correlation would indicate that station costs could be expressed as:

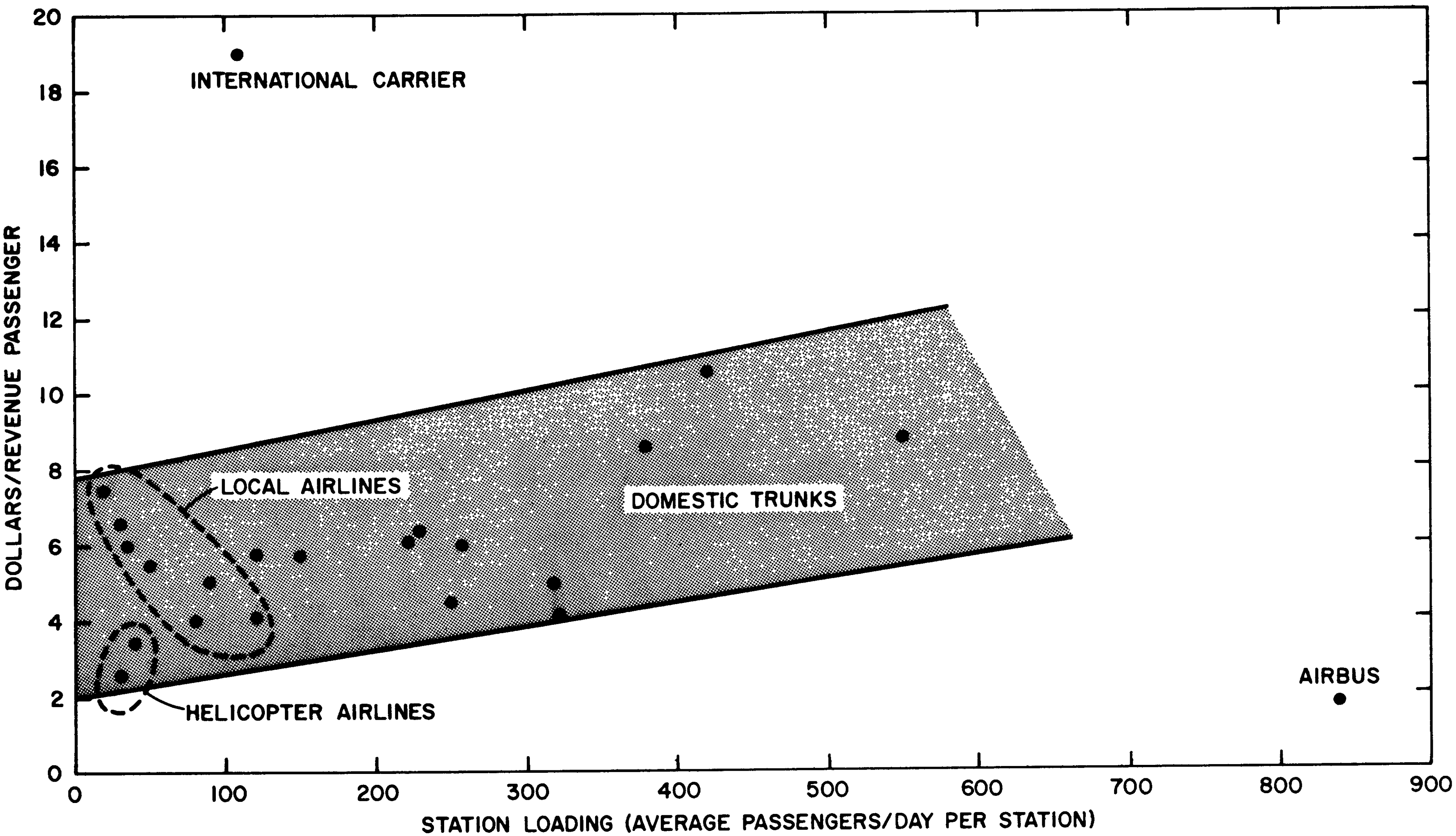

Figure VII-4. STATION OPERATIONS COSTS PER REVENUE PASSENGER vs STATION LOADING

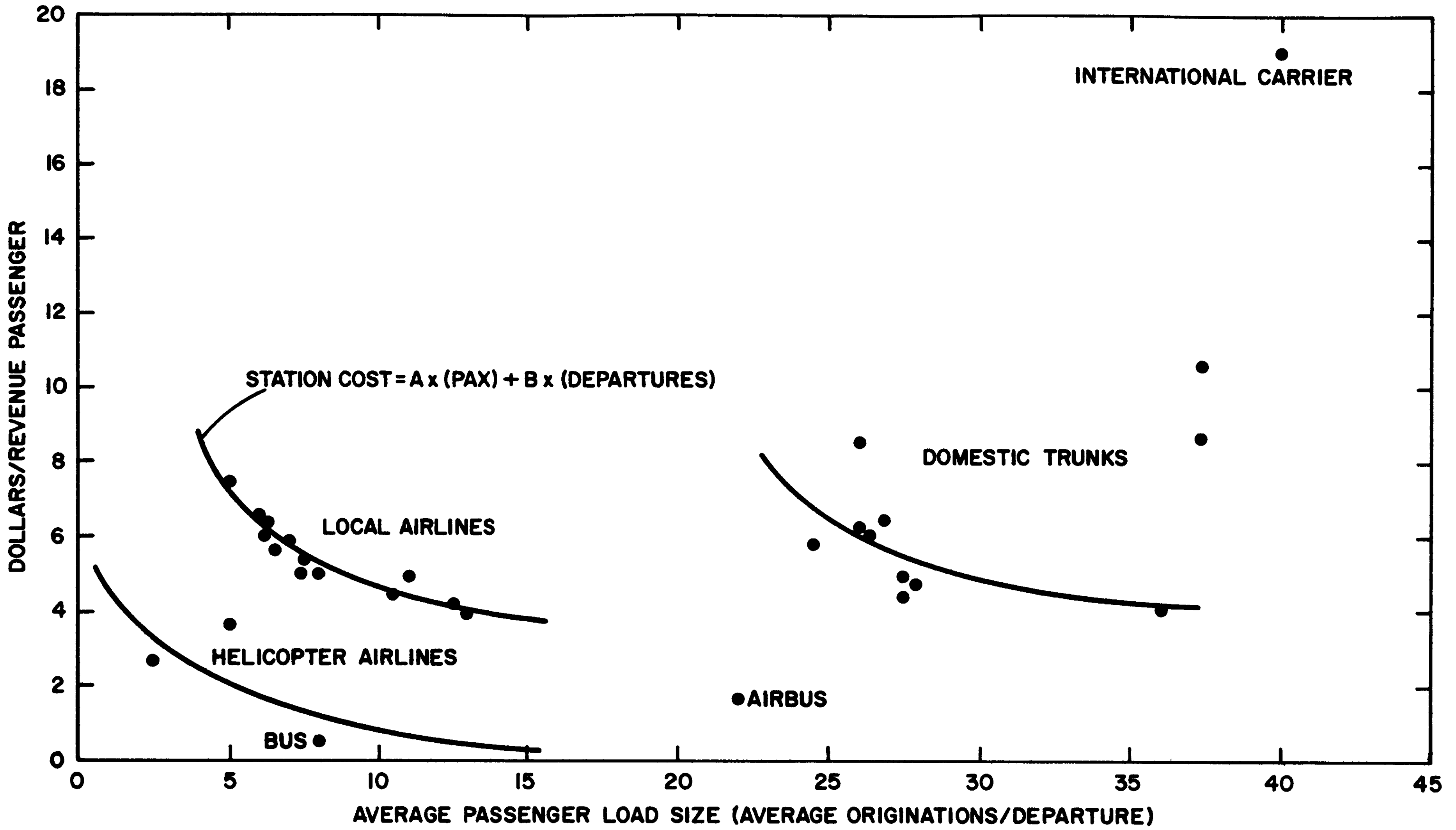

Figure VII-5. STATION OPERATIONS COSTS PER REVENUE PASSENGER-1964 (vs AVERAGE ORIGINATIONS PER DEPARTURES)

$$\text{Total Station Operations Cost} = A\ (\text{No. of Passengers}) + B\ (\text{No. of Departures})$$

where A and B are constants on the order of

$A = 2$ dollars per passenger

$B = 30$ dollars per departure

By examining Figure VII-5 it is obvious that other values of A and B would have to be used to describe the trunk airlines' higher costs, and also the helicopter carriers' lower costs. The number of ground employees at the stations, and the level of services performed for the passenger would seem to be important variables in determining the level of station operations costs for these various airlines.

At a similar value of average passenger load size, the bus carriers have costs which are lower by an order of magnitude over the local service carriers' costs. As previously mentioned, this is achieved through a large proportion of bus stop departures where a minimum of investment is made in buildings and equipment, and where leased personnel, or the bus drivers are used instead of station personnel.

TOTAL INDIRECT COST BREAKDOWN

While station operations costs are essential ground operational costs incurred in loading passengers, and handling the vehicles for any transport system, they represent only one-quarter of the airline indirect expenses. A total breakdown of the indirect airline costs has been estimated as shown in Table VII-3. The costs are expressed as unit costs in terms of dollars per passenger handled, dollars per aircraft departure, and dollars per revenue passenger mile (RPM). The airline information pertains to the top ten domestic trunk airlines as reported to the CAB for 1963. The helicopter airline information has been estimated from the carriers' accounting records, and the bus results estimated by using ICC information for Class I, Intercity Motor Carriers for 1961, allocating the expenses to the appropriate airline classifications.

The results show the wide variation in unit costs which are possible in different modes of transportation. The typical airline cost of $6.24 per passenger could not be tolerated in short haul helicopter and bus systems. Airline fares have a zero mileage price of around $5.00 per ticket to offset this cost. The helicopter systems, even at their low station densities and average plane load have lower costs. The bus carriers' results indicate that it is possible to provide minimal traffic service and negligible sales costs and obtain passenger handling costs of less than 50 cents per passenger.

Similarly, the cost per vehicle departure shows a wide variation from $142 per airline departure to $1.60 per bus departure.

Indirect Cost Breakdowns

Cost Category	Airlines 1963	Helicopter-X 1964	Helicopter-Y 1964	Intercity Class I Buses-1961	
Passenger Service (¢/RPM)	0.5	1.36	1.68	0.11	.18
Vehicle Servicing ($/departure)	92.30	3.08	0.76	1.17	5.12
Traffic Servicing ($/passenger)	2.89	1.48	1.12	0.35	.485
Sales Reservations ($/passenger)	3.35	0.66	0.92	0.12	.425
Advertising (¢/RPM)	0.18	0.24	1.09	0.05	.10
General Administration (¢/RPM)	0.25	3.92	6.73	0.26	.29
Ground Facilities ($/departure)	33.10	4.50	1.02	0.28	14.76
Landing Fees Road Tolls ($/departure)	17.05	0.17	0	0.232	0
Totals					
Passenger Handling ($/passenger)	6.24	2.14	2.04	0.47	
Vehicle Handling ($/departure)	142.45	7.58	1.78	1.60	
Overhead Costs (¢/RPM)	0.93	5.52	9.50	0.42	

TABLE VII-3

This variation is partly due to the complexity of the modern airline transport with its electronic, hydraulic, air conditioning systems, and their relatively low levels of reliability. It is also due to the greater number of departures from helistops and bus stops for the shorter haul systems. The reliability and maintenance problems of the current helicopter transport aircraft are very comparable to the airline transports, and the order of magnitude improvement in servicing costs can only be explained through the multi-stop, long haul flight patterns, and by the smaller investment in ground facilities required at these stops.

The remainder of the indirect costs are of an overhead nature, and for the purposes of this study have been allocated against the system's production levels of revenue passenger miles. Here the effect of scale is clearly seen where the rather small unproductive helicopter systems have very high costs compared to the larger airline and bus systems. For a short haul system, the passenger service costs can be minimized through eliminating meal and stewardess service. Passenger liability insurance seems much more expensive for the present helicopter airlines compared to airline and bus costs. Advertising, and General and Administrative costs are also high for the present helicopter systems. However, there is no reason to believe that cost levels equivalent to airline and bus systems could not be achieved.

A point to be made regarding the total indirect costs is that they are quite within the jurisdiction of management and marketing decisions. Lower levels of service and costs can be expected for short haul air systems, similar to other modes of short haul transportation, providing airline methods are not applied. For this reason, the V/STOL air system is best described as an "Airbus" system and not an "airline" system.

ANAYLSIS OF GROUND PERSONNEL REQUIREMENTS

Since a large proportion of indirect costs are salaries, an estimation of ground personnel requirements is necessary to predict the Airbus System indirect costs.

Station Operations Personnel at a Major Station

The Northeast Corridor airbus system envisaged has 13 major stations which would handle on the order of 6,000 passengers per day and 150 departures.

Traffic Servicing Personnel

At each departure gate, there would be two traffic agents each with a telephone, and reservation system agent set. Their duties would be ticketing and boarding of passengers during a departure, and acting as local reservations and sales agents between departures. The major terminals have 8 gates and an average of three shifts per day would be necessary to cover the period from 6 a.m. to midnight over the 7 day period.

No. of Traffic Agent Staff per station = 8 x 3 x 2 = 48

Aircraft Ramp Personnel

On the VTOL landing deck, there would be an average of 8 men to refuel, connect air conditioning and electricity from the hydrants, and assist the cabin crewmen in unloading the baggage. Using a factor of 3 for staffing,

No. of Aircraft Handling Personnel per Station = 8 x 3 = 24

Aircraft Dispatch and Communications Personnel

One dispatcher would be required in the tower cab to relay weather, flight plan information from the computer, record departure and arrival times, and control deck operations. During IFR, a second traffic controller would be necessary to handle approach and departure traffic, and would be useful during VFR busy periods to give relief and assistance. With two men present all times, and three shifts per day over a seven day week, the staffing factor is: $3 \times \frac{7}{5} = 4.2$.

No. of Dispatchers per Station = 2 x 4.2 ÷ 8

Station Operations Personnel at a Small Station

The remainder of the terminals in the Airbus System are simple stopping points to load and unload passengers and baggage. The aircraft is not normally shut down, refuelled or serviced. It is expected that these stations would handle roughly 150 passengers per day, and 15 departures. The average staffing for these terminals would be two traffic agents, who would assist the cabin crewman in unloading baggage, perform the ticketing and boarding process, handle local reservations and sales by telephone, and any necessary dispatch duties. At very small stations, there would be only one agent on duty at all times, and the appropriate staffing factor is 4. Backup traffic agent personnel can be flown in from major stations for peak conditions, or sickness.

No. of Traffic Agents per Minor Station = 2 x 4.2 ÷ 8

Passenger Service Personnel

It is deemed necessary to have one male cabin crewman on board each aircraft to answer passenger questions, close the door, check seat belts, and load and unload baggage at each stop. This man would be well trained in emergency procedures, and strong enough to manhandle both passengers and safety equipment in an emergency. He could be either a pilot, and thus provide relief to the pilot crew during their multi-stop tour of duty, or perhaps a servicing mechanic as a dual role to serving as cabin crewman.

The requisite number of crewmen can be estimated by knowing the fleet size, and using a staffing factor for each crew position. This factor can be checked through using the yearly utilization of vehicles and crew. At 3,000 hours per year for vehicles and 80 hours per month for crew, the factor is $3{,}000/(80 \times 12) = 3.1$. The historical ratio of pilot crew to aircraft for U.S. domestic trunks give 3.2.

Assuming a 60 aircraft fleet the

$$\text{No. of Cabin Crewmen} = 60 \times 3.2 = 190$$

Reservations and Sales Personnel

There are no local sales offices. All local sales are done at the stations by the traffic agents. These traffic agents can also handle reservations and information telephone calls, but at boarding times, they will have these calls automatically shunted to a central reservation facility for the whole system. Using the American Airlines Sabre loading information as an indication of peak calling demands, we could expect peak rates of 100 calls per minute for the 16.7 million passengers per year system. At roughly one minute per reservation call, there will have to be 100 agent sets plus personnel at the central facility. It is expected that at Christmas, Thanksgiving and holiday weekends, passengers will realize the problem and make reservations for their travel even though it will cost them an extra surcharge. These peak operations determine the maximum size of the reservations facilities required. It is expected that throughout the year, the normal passenger behaviour in the high frequency Airbus System would be not to make reservations except to connect with a scheduled airline service. Thus, the central facility would on the average require staffing of the order of 33 positions, and with a factor of 3, would give a total staff of 100 at the central facility.

No. of Reservations Agents at Central Facility = 100

General and Administrative Personnel

The management information system should allow efficient, modern management techniques to be applied with a smaller staff. Some functions like accounting, economic analysis, inventory analysis, maintenance recording, etc. can be simplified and automated with data entered only once at the agent set sources in the field, thereby eliminating the multiple handling, and classification of data by clerical staffs in present airline practice. On the other hand, there will be more use of programmers at a higher salary. Functions such as Purchasing, Training, Legal, Public Relations, etc. will require a similar number of personnel as present airline systems. The total administrative personnel is estimated as 650 on the basis of a percentage of total personnel equivalent to present short haul airline systems.

Total Airbus System Personnel

On the basis of 13 major terminals (including 5 major airport maintenance bases) and 37 minor stations, and a 60 aircraft fleet, the following total system personnel are estimated:-

Traffic Servicing Personnel - 20%

Major Stations (48) x 13 = 624
Minor Stations (8) x 37 = 296

920

Aircraft Servicing Personnel - 9%

Major Stations (24 + 8) x 13 = 416
Minor Stations (0) x 37 = 0

416

Passenger Service Personnel - 4%

Cabin Crewman = 190

Reservations Personnel - 2% = 100

General and Administrative - 14% = 650

Pilot Personnel - 8.5%

(Pilots (60 aircraft x staffing factor of 3.2) = 190
Co-Pilots (60 aircraft x staffing factor of 3.2) = 190

Maintenance Personnel - 41%

(Based on historical airline ratio of mechanics to aircraft = 21, plus a 50% burden for staff) = 1,890

TOTAL System Personnel	4,546

Examining the measures of productivity for the airbus system (see Figures VII-1, VII-2, pages 11 and 13) there are 3860 passengers per employee (a value slightly less than the bus lines), and about 660,000 revenue passenger miles per employee. This is twice the bus productivity (due to an average passenger trip of 180 miles compared to a bus figure of 85) and also twice the productivity for the trunk airlines.

ESTIMATION OF AIRBUS SYSTEM INDIRECT COSTS

By using the present airline average salary of $8,000 per year (versus the average bus employee salary of $6,500 per year) to estimate ground personnel salaries, and maintaining airline ratios of non-salary expenses in each of the indirect expense categories, an estimate of the indirect costs for the Airbus System can be made.

Passenger Service

The non-salary portion is mainly passenger liability insurance. It has been assumed that equivalent airline rates can be obtained. The cabin crew salary costs plus 10% for supervision, administration and training can be estimated from the staffing.

Cabin Crew Expenses	= 0.05¢ per RPM
Passenger Insurance (+ Miscellaneous)	= 0.13¢ per RPM
TOTAL	= 0.18¢ per RPM

Total Passenger Service costs are 0.18¢ per RPM which is roughly equivalent to the bus costs given in Figure VII-3 (page VII-14).

Aircraft Servicing

The salary expenses of ramp and dispatch personnel constitute the sole expense in this category. Servicing administration costs are taken as 10%

Ramp Personnel Expenses	= $3.77 per departure
Dispatch Personnel Expenses	= 1.25 per departure
TOTAL	$5.02 per departure

This expense is greater than the equivalent bus operation reflecting the necessity of the aircraft to be met by a crew of aircraft handlers. The effect of bus stop operation makes the level of costs resemble the helicopter costs rather than the large airline costs in Table VII-3, page VII-21.

Traffic Servicing

Although the traffic agents are also performing a sales function, their total salary will be charged to this function. Servicing Administration costs are included at 10%.

Traffic Agent Expenses = $0.44 per passenger

This expense is similar to the bus level of expenses, and much lower than either the airline or helicopter system expenses. This is mainly due to mechanized passenger handling at the larger terminals, and the higher station loadings at the smaller terminals.

Reservations and Sales

The airline breakdown on these costs are: internal reservations and sales costs, 67%; communications costs, 10%; and external commissions to travel agenst for ticket sales, 23%. In the Airbus system, there are 100 central reservations staff for reservations only, and the traffic agents for sales. Part VI has estimated the cost of a reservation at $0.225 per passenger and from the previous section, costs for the traffic agents are $0.44 per passenger. The proportional commissions costs would therefore be $0.20 per passenger.

Reservations Cost (from Part VI)

Central reservation staff	\$0.05 per passenger
Central computer facility-$\frac{1}{2}$ amortization	0.075 per passenger
Communications Costs	0.10 per passenger
Travel Agents Commissions	0.20 per passenger
TOTAL	\$0.425 per passenger

This cost is higher than the equivalent bus costs where a reservation system and computer are not maintained. The costs are much less than the present airline costs due to the lack of local sales offices, and slightly less than the helicopter costs. Because the air vehicle direct costs at \$1.50 per mile are much higher than the corresponding bus operating costs (\$0.20 per mile), it is more important to achieve efficiency in terms of utilization and load factor in the air systems, and some expense is generated in achieving this efficiency. Attempting to calculate this trade-off is a difficult task, and it has been decided to use the modern management information system approach for the Airbus system. A high frequency air commuter system, on the other hand, would probably not need reservations and the computer system.

Advertising

A level similar to the present bus advertising is assumed.

Cost of Advertising = 0.10¢ per RPM

General and Administrative

The airline ratio is 75% salaries and 25% miscellaneous expenses. For the Airbus system, there will be a larger proportion of programmers and less clerical staff due to the management information system. The average salary has been increased to $10,000 per year to reflect this change.

Administrative Salaries = 0.22¢ per RPM
25% Miscellaneous expenses = 0.07¢ per RPM
TOTAL = 0.29¢ per RPM

This cost level is slightly more than the present airline and bus system cost levels. It is much less than the small system helicopter expenses. See Table VII-3, page VII-21.

Ground Facilities

The amortization and maintenance expenses of the station facilities have been calculated in Part V. The minimum estimate (which does not amortize the land costs and assumes concessions revenues for the major terminals) will be used here. The VTOL and STOL terminal costs will be estimated separately, and the unit cost will be based on dollars per departure.

The remaining amortization costs for the headquarters building and computer system (½ has been allocated to reservations costs) are overhead costs. Along with the maintenance facility costs (which have been estimated in Part V), they are stated in terms of dollars per departure for comparison with Table VII-3.

VTOL Ground Facility Costs

Terminal Operating Costs	$ 8.20 per departure
Headquarters, Computer System (½)	1.75 per departure
Maintenance Facilities	4.81 per departure
TOTAL	$14.76 per departure

STOL Ground Facility Costs

Terminal Operating Costs	$12.60 per departure
Headquarters, Computer System (½)	1.75 per departure
Maintenance Facilities	4.81 per departure
TOTAL	$19.16 per departure

These costs per departure compare with the domestic airline value of $33.10 per departure given in Table VII-3. The difference is mainly due to the preponderance of small stopping points in the terminal operating costs. The value compared to the bus figure of $0.28 per departure is very unfavorable. The difference is caused by much smaller, or zero bus stop investments and the much reduced requirement for investment in hangars and overhaul bases. This latter is a direct result of the increased complexity of the air vehicles' maintenance compared to bus maintenance procedures.

Landing Fees

It is expected that at airport sites the local authority will assess the Airbus System on a comparable basis to the airlines. However, in determining the investment costs of ground facilities, the construction of landing pads and runways have been assumed. If the local authority assumes this cost, it is entitled to charge an equivalent cost in landing fees. The landing fee costs are therefore taken to be zero on the grounds that an equivalent cost has been introduced into the ground facilities' category.

Total Airbus System Indirect Costs

For comparison with Table VII-3, the Airbus system costs can be summarized as follows:

Passenger handling = $ 0.865 per passenger
Vehicle handling - VTOL = 19.78 per departure
- STOL = 24.18 per departure
Overhead Costs = 0.57¢ per RPM

For direct application with the direct operating costs, these costs can be converted to costs per available seat versus trip distance. The two costs, passenger and vehicle handling, are incurred at zero range. With an 80 passenger vehicle and an average system load factor of 60%, the above costs give a zero range cost per available seat equal to \$1.04 for the VTOL system, and \$1.16 for the STOL system. The overhead variation range for the system which produces 3×10^9 revenue passenger miles at 60% load factor gives a rate of 0.34 cents per available seat mile. The resulting variation with trip distance of indirect costs per available seat is shown in Figure VII-6 along with the comparable helicopter, and bus system costs.

CONCLUSIONS

For successful operation of any short haul passenger transportation system, low costs in terminal operations must be achieved. The U.S. Intercity Bus Carrier costs demonstrate the possible levels to which these costs can be reduced.

An air system, with its more complex vehicle and terminals can approach the bus cost levels by adopting bus type operations where multi-stop, line haul service is provided between major terminals. The VTOL Airbus System, with short air and ground maneuvering times has the potential of providing this type of service.

With a much higher productivity for the ground employee provided by terminal design and a modern management information system, the indirect costs of a short haul Airbus System can be reduced to a fraction of present airline costs. The bus costs, which are still lower, are probably not a desirable level of service and comfort to the modern passenger traveling within the Northeast Corridor.

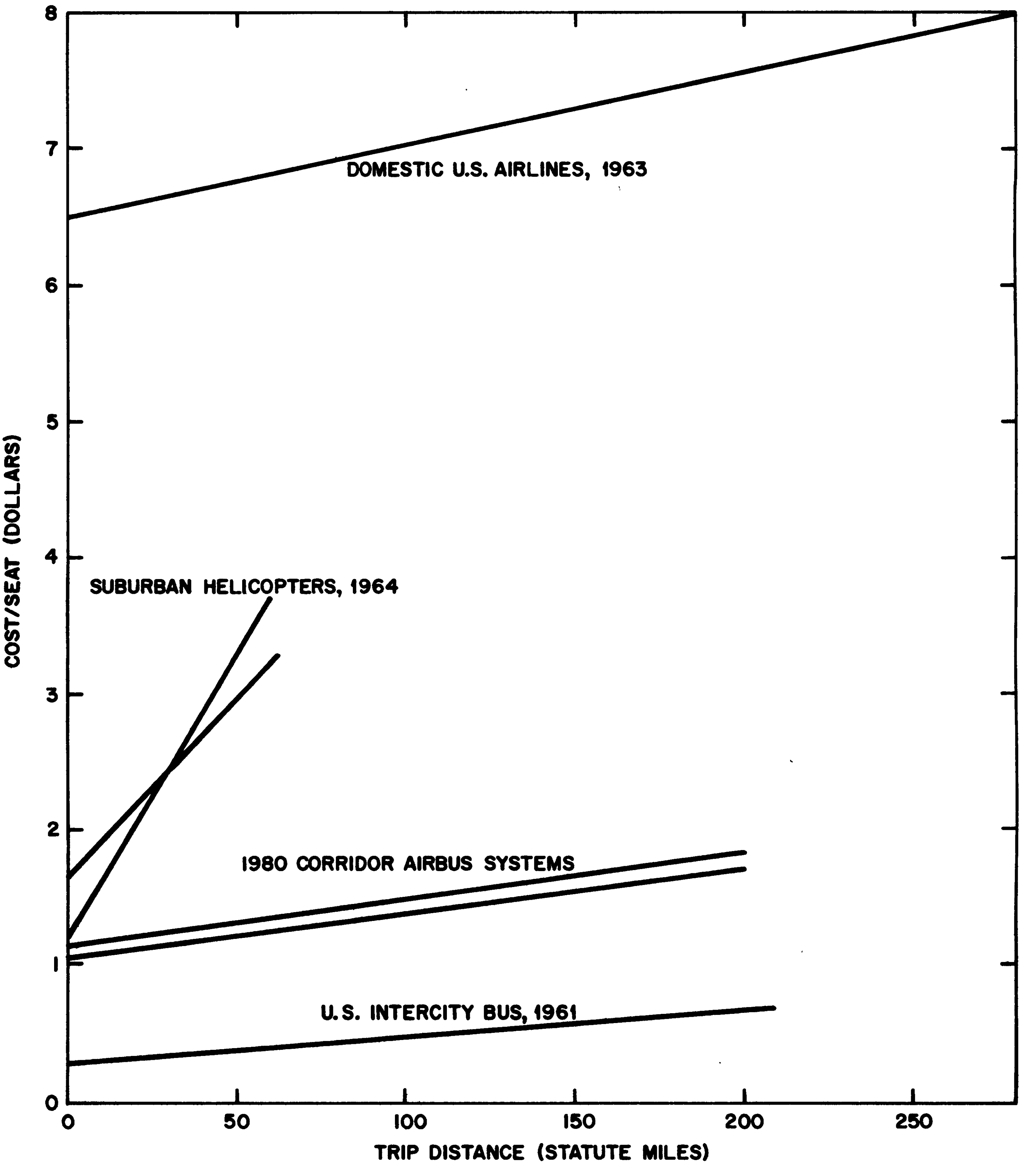

Figure VII-6. INDIRECT TRIP COST PER AVAILABLE SEAT

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VII-2 Facts and Figures, Air Transport Association of America, 1962 1963, 1964.

VII-3 Exhibits to CAB for Hearings on Permanent Certification, Los Angeles Airways, July 1965.

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PART VIII.

OPERATING CHARACTERISTICS OF THE AIRBUS SYSTEM

TABLE OF CONTENTS

THE SYSTEM CONCEPT

As a result of studying the problem of air transportation in the 1980 Northeast Corridor, a concept of this system and its operating characteristics has been developed. This section will briefly describe that concept.

Air Operations

The air system will serve all major centers of population within the Corridor with a high frequency, city center service operating from small heliport or vertiport terminals, or from major airports to provide an interface with the longer range airline system.

The scheduling would consist of a high frequency fixed, published schedule backed up by a floating schedule of extra sections to meet daily variations in demands. Good traffic data would be gathered using a computer information system to record true demand and, thereby, adjust daily fixed schedules in order to obtain values of vehicle utilization and system load factors, such as to optimize profit. The flights will consist of line haul, multi-stop segments between terminals, with very short (one minute) stopping times at intermediate, "bus stop" type terminals. Refueling, servicing, etc. would only take place at major terminals.

These very short haul VTOL vehicles are rather large by present standards of the order of 80 or more passengers and would have speeds from 200 to 400 knots. For safety reasons, they should be multi-engine vehicles capable of single engine-out takeoff and hover at low altitudes. Because of city center operations, their noise level should be made as low as possible by keeping rotor or propeller tip speeds below .85M.

In normal VFR, good weather operation (which describes better than 90 % of operating time), flights shall proceed directly from terminal to terminal with no air maneuvering or following of air traffic routings. Flight plans will be VFR direct, and special VFR if possible. For the VTOL aircraft, approaches to landing will be made from the enroute direction independent of wind direction. Landing pads will be assigned by the deck controller at five miles to avoid conflicting paths and provide working of other VFR, low altitude traffic. At busy airports, the fixed wing landing and takeoff patterns will be avoided, causing some minimal air maneuver time through the airspace restrictions. For the STOL aircraft, similar traffic patterns to arrange for spacing on final approach and the runway will be necessary. If a normal square landing pattern is flown, the STOL aircraft will proceed to the downwind leg for sequencing, crosswind leg for spacing, and final approach to the wind direction runway. This procedure will add five minutes of air maneuver time to each flight and has been assumed in the ATA costing. As well, there can be an air delay time, and a ground delay time of significant size if the regular fixed wing patterns are entered at major airports and runways are shared with regular traffic. These air traffic assumptions are critical to the economic success of the short haul system and further study is warranted. The terminal area design at New York must take into account the existence of a high volume of V/STOL traffic into the present and future airports, and other urban locations.

In IFR bad weather conditions, it has been specified that the system be capable of operation down to 50 feet visibility, and winds of hurricane strength. This places stringent requirements on the vehicle control, stabilization, guidance, and navigation subsystems in order to perform approach and departure operations at high frequency while maintaining a level of safety comparable to today's airline standards. With the continuing research and development of commercial and military systems, it is believed that these requirements will be easily satisfied by 1980. The VTOL air transportation system can be designed to have a better operational reliability (a goal of 99.5% in this report) than the high speed ground transportation systems (other than enclosed tube, or underground right of way systems) which are affected by snow,ice, and wind at the high ground speeds contemplated.

Ground Operations

In keeping with the very short haul nature of the system, the ground operations have been kept simple by reducing services to the passenger and using the computer system for sales, boarding and reservations. No in-flight meals or entertainment have been contemplated, seats have assumed lighter because of short trips, and cabin attendants reduced to one man.

To interface with the airline system, and allow an air passenger to insure connections, a reservations service has been retained at a surcharge to the passenger payable in advance. This also provides for efficient advance planning of system capability at peak holidaytimes, where it is assumed everyone will make reservations to ensure a seat. The normal mode of operation expected will be a standby boarding where the no-reservations passenger arrives at the terminal and checks in up to 20 minutes before the flight when the load control is given to the departure gate, and reservations cease. The transfer of load control is made after the vehicles'previous departure, using the computer system. This is necessary due to the multi-stop character of the flight segments. Terminal computer-driven displays will indicate the stopping points of each flight and the remaining available seats to each point.

At major terminals, baggage (due to the airline passengers in the system) will be taken from the passenger and delivered to him in the terminal (perhaps at some extra charge) in order to avoid delaying the loading and unloading process. At minor terminals, where passengers disembark onto the ramp, baggage will be walkon with the cabin attendant sorting, loading, and unloading into bins beneath the vehicle floor similar to present bus methods. It is expected that the average bags/passenger will be low similar to present air shuttle experience.

Terminals will be sited in and around major population areas, both city center and suburban, at major airports and at smaller cities in the Corridor. VTOL sites will be much easier to establish throughout the Corridor due to the smaller land areas required, and the presence of water marshes, railroad yards, dock areas, expressways, etc. for approach, departure paths which can still be found throughout the region. A major effort should be made to construct transportation centers in the major cities to allow interface between bus, rail, subway, taxi, and the airbus system. Suburban terminals would have large parking lots to accomodate the airline passenger and city center sites could be parking garages.

An important assumption in the system concept is that the passenger system should handle large volumes in order to spread the overhead costs of maintenance, ground facilities, administration, etc., and allow large volume methods and facilities to realize efficient operations and low cost. It has been assumed that all of the intra Corridor air travel and a proportion of bus and auto travel is carried in order to demonstrate that the resulting cost and convenience would be attractive enough to the average Corridor passenger, and perhaps to the commuter. Commutation by air has not been assumed, although with the low ground or indirect costs of such traffic, it is a definite possibility.

NOISE CONSIDERATIONS

Operation from city centers and especially from suburban sites will cause problems unless the noise generated by VTOL vehicles is kept below ambient noise levels. An operational factor which has been found important to present airport operations is the frequency of service along the approach and departure paths to the active runway. With the VTOL aircraft approaching along multiple paths, the complaints generated outside the immediate vicinity of the site can be expected to be reduced.

The noise generated at the site is a function of vehicle gross weight and the hovering tip speed. Present, or projected large helicopters can be below ambient noise levels at city center sites, and certainly will be the quietest VTOL vehicles. If tip speeds are kept low, the tilt wing can be reasonably quiet, but a major problem is expected from the jet lift vehicles. Recent experience has shown that this may not be insoluble. Treatment of the compressor inlet, the highly directional nature of the jet lift noise pattern and the use of a moderate amount of bypassing may reduce the noise to a tolerable level for some city center operations.

The site itself must be chosen to avoid disturbing noise sensitive areas, such as hospitals, or schools, and much can be done in site preparation with sound baffling fences, and sound absorbers designed into the landing pads, using grill covers and downwash, or jet blast channels in the pad.

SAFETY CONSIDERATIONS

A level of safety similar or better to present airline safety will have to be achieved to ensure passenger acceptance. Multi-engine vehicles, two pilots, redundant aircraft control systems, and all present aircraft design practices have been assumed to apply in the operation of this system. It is expected that full investigation of all accidents would find the system weaknesses and bring rapid design remedies. Safety in system operations is only achieved by such a process, and the operators, manufacturers, and governmental agencies can be expected to continue to work towards the safest possible system.

ALL-WEATHER RELIABILITY

In order to produce a system of transportation of equal reliability to various ground system (as well as the 1980 airline system), it is mandatory that the V/STOL air system be capable of all-weather operation with no undue delays due to reduced system capacities. This requirement specifies certain capabilities for the following subsystems, in order to produce an IFR, all-weather blind landing vehicle:

1) The Air Traffic Control System
2) The Vehicle Guidance System
3) The Vehicle Control System
4) The Vehicle Weather Systems (anti-icing, visibility, etc.)

Since it is unrealistic to define all-weather as being absolute zero/zero conditions where the surface movements of automobiles and taxiing aircraft would be nil, it is defined as being conditions down to 50 feet visibility. Assuming a 50-foot visibility, the system would be able to operate more than 99.5% (Reference VIII-3) of the year for average conditions over the Northeast Corridor.

Present All-Weather Air Transportation Problems

There are at present serious bad weather operating problems for fixed wing aircraft, particularly in the New York area. The occurrence of any form of precipitation, or lowering of the ceiling to the point where the IFR-ILS procedures must be relied upon reduces present airport capacities to the point where regularly scheduled traffic cannot be handled. At these times, the air traffic control centers will affect "flow control" procedures whereby only limited access to the congested area is available and all residual flights are kept waiting at their departure airports. Despite this measure, service delays still occur both in the air awaiting to land, and especially on the ground where takeoff aircraft are attempting to fit into gaps in the landing flow (Reference VIII-7). Any extended period of such operations seriously disrupts the entire U.S. airline system with aircraft arriving late, departing late, and proceeding to other destinations for refueling. The effects of a bad day at New York disrupt services across the whole country and even into Europe.

While the airlines will develop the capability for blind landings before 1980, this congestion will still occur and it represents a serious restrictions upon the further growth of airline transportation. The congestion is caused by the reduction in system traffic capacity when using bad weather procedures. Where a good day will see airport operations at a rate of 90 or 100 operations per hour with two or three runways being used, a bad day will restrict landing operations to one ILS runway, with other runways being used for takeoffs, at a rate of 30-40 operations per hour. The blind landings will still occur on this single runway, probably at reduced operational rates if visibility on the ground is low, and, therefore, no relief from the traffic congestion is obtained by the introduction of blind landing equipment.

The need is clear for simultaneous operations on two runways at our major airports or construction of more airports to spread the traffic load. Unfortunately, neither solution seems very probable due to the lack of precision guidance equipment to allow safe parallel operations and the political problems of placing a new major airport within a reasonable distance of present city centers.

This reduction in capacity for the fixed wing aircraft can be traced to their dependence upon a runway for landings and takeoffs. Both the air maneuvering and landing guidance problems, and the difficulties in siting new airports are caused by the necessity to have a windward strip of land about 10,000 feet in length. With a reduction in the land requirements and a capability of approaching the terminal from all directions, these problems are alleviated. With the VTOL aircraft, multiple landing pads can be operated simultaneously at one site, thereby increasing its bad weather capacity, and eliminating delay in bad weather services. By dispersing these sites and capturing the short haul market for air travel within the Corridor, the traffic load (and thereby the delays) at the present Corridor airports can be much reduced, and they can be allowed to serve their proper market, the long haul passenger who is leaving or entering the Corridor area.

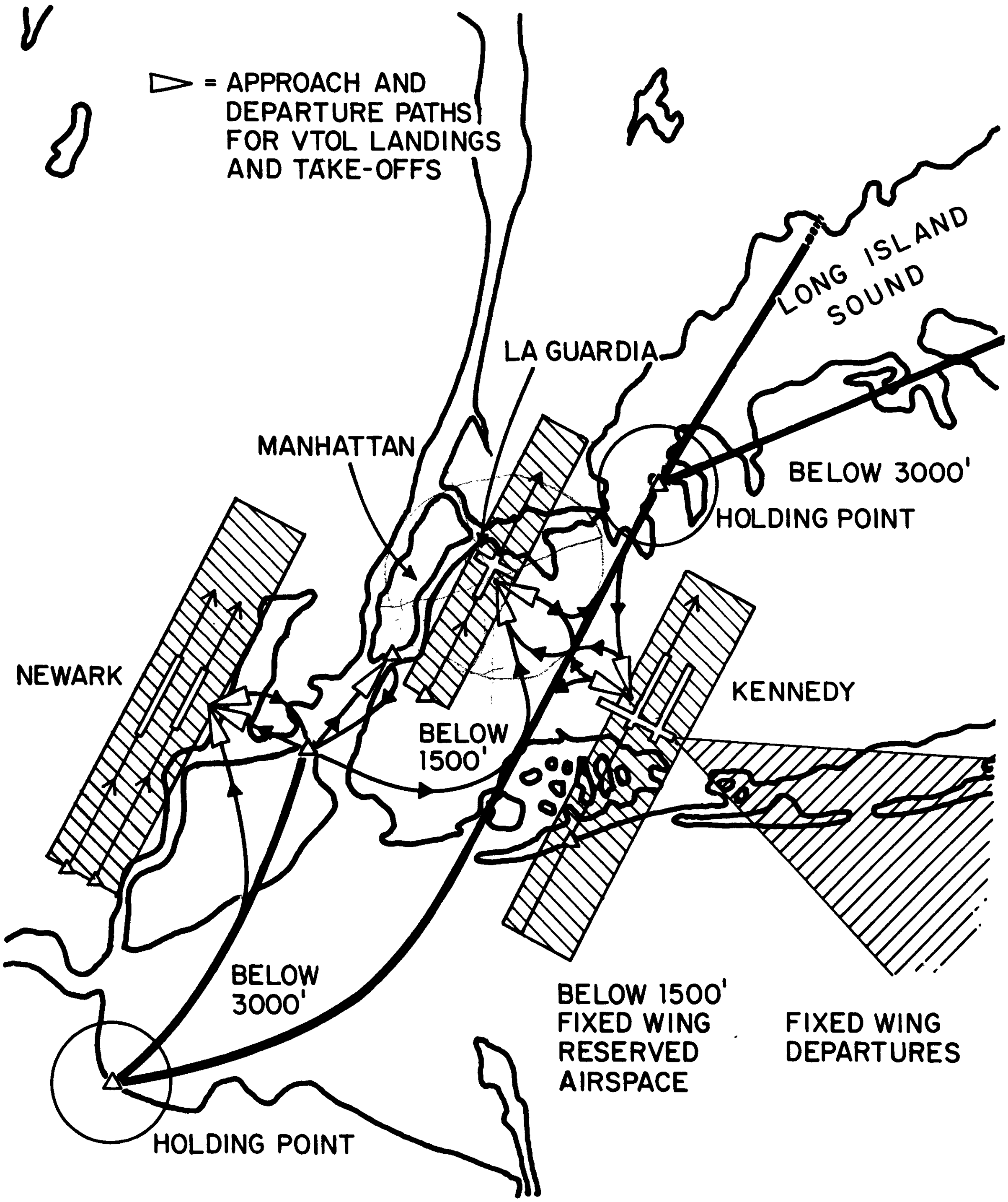
For these reasons, the all-weather, high capacity capabilities of the short haul air system become mandatory. Fortunately, military reasons are causing development of automatic subsystems which will provide the VTOL system with these necessary capabilities. This increased bad weather system capacity places the VTOL vehicles in a preferential position relative to STOL vehicles for adoption by the Corridor air system. However, the problems of both VTOL and STOL vehicles are discussed in the following sections.

The IFR Terminal Area

In order to avoid becoming involved in the IFR procedures of fixed wing air traffic in the congested area surrounding major airports, V/STOL traffic routings around and under the fixed wing traffic patterns would be necessary. An example routing pattern is indicated in Figure VIII-1 for a V/STOL aircraft operating into various points in the New York area.

FIGURE VIII-I

VTOL IFR BAD WEATHER ROUTINGS - NEW YORK AREA



V/STOL traffic remains segregated underneath the regular arrival and departure flows, and reaches the airport terminal buildings on approach and departure paths roughly at right angles to the ILS Instrument Runway direction. Although the short haul nature of the trips combined with the computer dispatch system would allow flow control methods to alleviate congestion of V/STOL air traffic, low level holding patterns are necessary to provide airspace for delaying aircraft in the event of the disruption of service at the terminals, etc. The VTOL aircraft would not hover, because of high fuel consumption, but would fly a holding pattern similar to fixed wing vehicles. The routings shown are used only in bad weather (probably less than 5 percent of the time). When VFR or special VFR conditions prevail, the Airbus system aircraft fly directly between terminals.

In order to establish safe low level routings for bad weather, good aircraft guidance and navigation are required. It is desirable to be able to define and follow three dimensional routings, with automatic tracking to within 1,000 feet laterally. A self-contained or area type (such as Decca) navigation system is desirable to allow flexible definition of these low level approach routings both in the metropolitan terminal areas, and at various outlying terminals within the Corridor. Accuracy in height keeping to within ± 10 feet using a hybrid barometric-inertial altimeter and radar altimeter for terrain clearance along with automatic height keeping equipment, is necessary to allow safe vertical separations of 500 feet between VTOL traffic on these low level routings, and insure accurate flare and hover information while blind flying. Velocity with reference to the ground is necessary for complete stabilization and can be used to give constant ground speed for traffic control purposes and accurate conformance to ETA's (Estimated Time of Arrival) to within ± 0.1 minutes in order to obtain good spacing of landing traffic.

The accuracy requirements stated above are determined by safe separations from other V/STOL aircraft and buildings in the city center areas, as well as by spacing requirements to maintain full traffic flow capacities. The automatic requirements arise from relieving the pilots from duties involving the control, guidance, and navigation of the aircraft in order to reduce the pilot workload and allow them more time for command duties and communication with ATC. The capabilities of the aircraft and their subsystems will make precision instrument flying in the terminal area substantially easier and safer in spite of the increased accuracy requirements. Standard traffic procedures are necessary to provide for training of pilots and ground controllers, and to permit organization of the IFR V/STOL traffic.

The type of procedures established are a direct result of the total system capabilities in insuring safety of operations. With good conformance on the part of V/STOL traffic to planned routings and times, these procedures can be simplified, and lesser communications required. It is assumed that the V/STOL terminals are not open to general aviation traffic, and that V/STOL transport aircraft will not enter the area without adequate navigation performance to guarantee the safety of these procedures.

Bad Weather Approach to Landing

In order to carry out the precision navigation and guidance required to land safely in poor visibility, a well-defined, straight approach path of a few minutes duration is necessary for both VTOL and STOL aircraft. Sufficient time is required to acquire and stabilize on this approach path for both manual and automatic approaches. Position information and tracking accuracy of the order of ± 10 feet is required along the approach path to insure a successful landing. To obtain this accuracy in automatic tracking in the face of wind changes, measurement of lateral velocity and acceleration with reference to the ground is necessary.

STOL Blind Approach

For fixed wing aircraft of 1980, an advanced Category III version of the ILS all-weather landing system will be available. The geometry of the approach is similar to that shown in Figure VIII-2. It is a low angle, 2.5° to 3° glide slope approach, about five miles in length, with an inner marker at 50 feet altitude to indicate flare height and the start of the runway. Runway lighting is mandatory including approach lighting beyond the runway. Overshoot, or missed approach procedures involving the airspace beyond the runway are necessary. Equipment is available commercially at the present time to perform blind approaches both manually with appropriate flight direction displays and also automatically through coupling to the autopilot right down to a landing, and by 1980 improvements in the path stability and tracking accuracy are expected. Because of the low approach speeds which cause sensitivity to wind effects, such improvements may be required for STOL aircraft. To provide complete coverage in varying wind directions, more than one ILS instrument runway per site is necessary. The other runway would be used for takeoffs during blind landing conditions.

Since the 3° approach path crosses the end of the runway at 50 feet, and intersects the ground at a point displaced by roughly 1,000 feet from its end, it is likely that the STOL aircraft will approach at approximately 6° (60 knots and 600 fpm. rate of descent) to reduce IFR runway requirements.

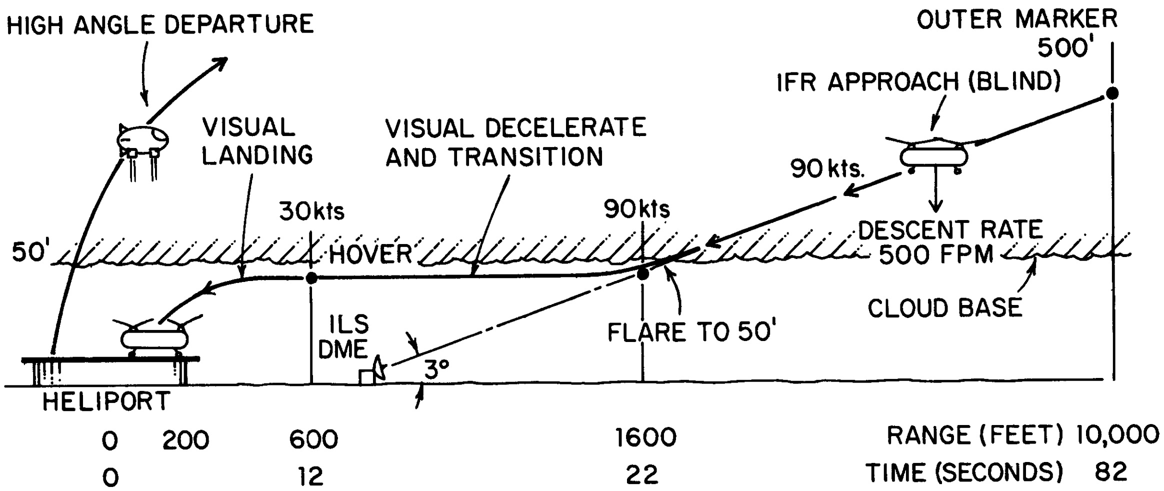
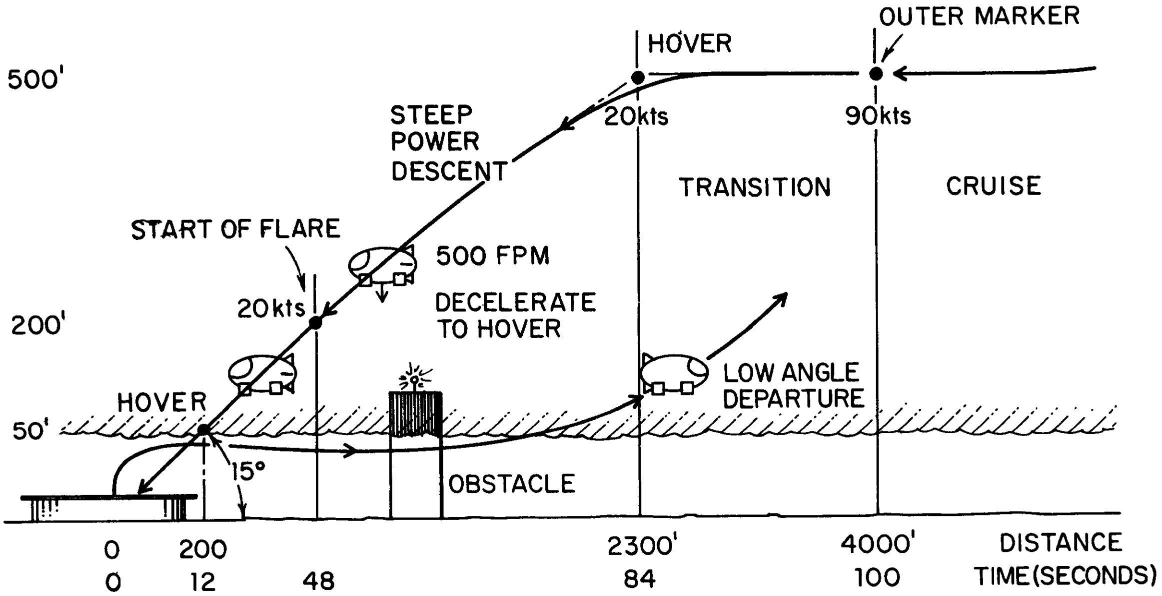


FIG. VIII-2 LOW APPROACH ANGLE, VISUAL TRANSITION AND LANDING.



HIGH ANGLE APPROACH FROM HOVER

FIG. VIII-3 IFR APPROACH PROFILE - VTOL TRANSPORT AIRCRAFT

The ILS technology presently exists to provide this steeper approach angle for the STOL.

VTOL Blind Approach - Low Angle (Figure VIII-2)

The low angle VTOL approach is an adaptation from the fixed wing procedures. A low angle approach at a flying speed with suitable handling qualities, and low fuel consumption and noise is flown down to 50 feet height. Transition is accomplished while flying level at this height ending at a hover point just short of the landing pads. No missed approach procedure is necessary as corrections should be possible at this point and the touchdown on the landing pad is performed visually with the aid of lighting and fog dissipation. The VTOL approaches can be independent of wind strength, direction or gustiness through the use of stabilization equipment which uses ground referenced velocities and accelerations, thus allowing use of a single approach path, or the simultaneous use of multiple approach paths. The stabilization, and guidance equipment to carry out such approaches either automatically, or with the pilot guiding a stabilized vehicle using suitable displays is under development for military systems now, and further developments can be expected by 1980.

VTOL Blind Approach - High Angle (Figure VIII-3)

To avoid carrying out the transition at a low altitude, and provide clearance over obstacles to an approach path, a high angle approach path is possible with VTOL vehicles. Figure VIII-3 shows the transition at 500 feet altitude from cruise to a power descent along a 15° glide slope. At 200 feet altitude, a deceleration along the glide path is initiated to come to the same hover point at 50 feet altitude just short of the land pad. The steep approach is dependent upon handling qualities under such flight conditions, and involves higher noise and fuel consumption. Rates of descent of the order of 600 feet per minute implied by this approach profile are well within the capabilities of present day helicopters without entering into the "vortex ring" conditions. Although the vortex ring condition is unlikely to be a problem for the higher disc loading tilt wing aircraft, wing stall problems could limit the rate of descent. Tests on two recent tilt wings, however, have indicated that the conditions assumed are well within the useable flight envelope.

This high angle procedure does reduce the size of the approach path, but not necessarily the time on approach. Variable glide slope ILS type equipment now exists, and can be applied to a commercial system for 1980.

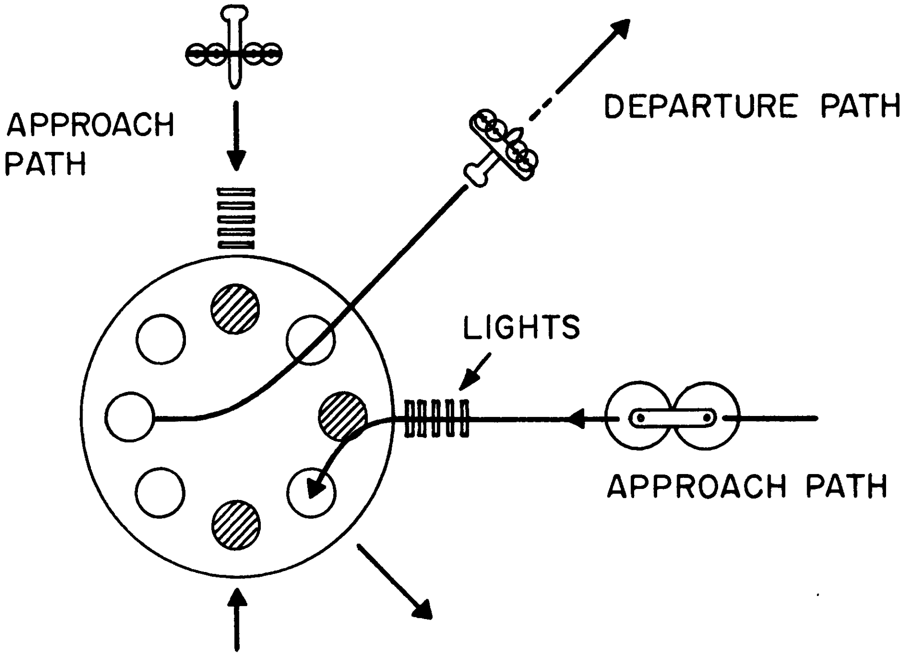
Landing Operations

STOL

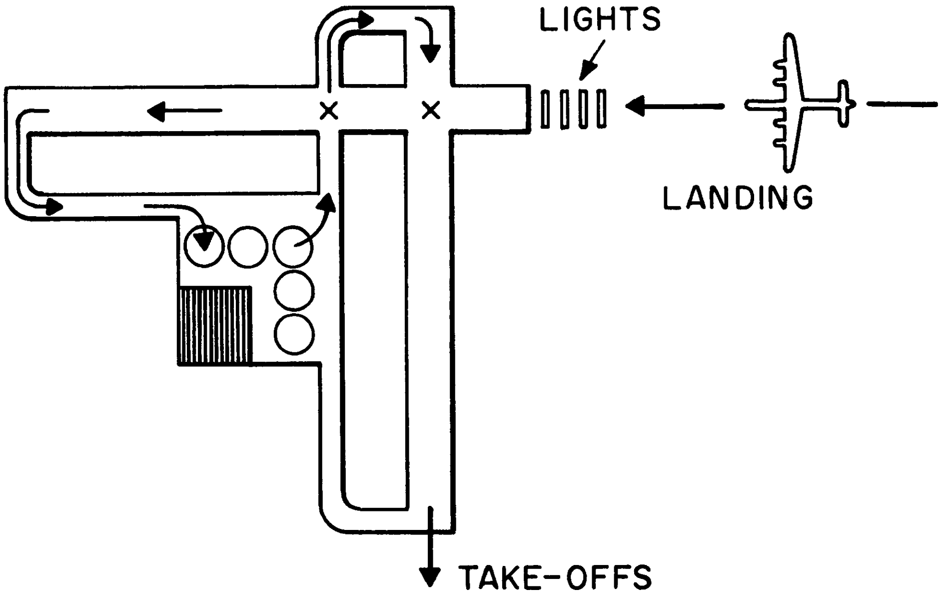
For the STOL and fixed wing aircraft, landing in 50 feet visual range will require instrumentation for runway centerline guidance and information on distance remaining and stopping performance. Good lighting can be used for the taxiways which are necessary to maintain landing capacity by clearing the runway as soon as possible. Approach lighting and runway lighting will be required as specified by present Category III regulations. This will require a clearway previous to the runway to install the lights. During winter, some methods of keeping runway and taxiways clear of ice and snow will be necessary.

VTOL

It is proposed that the landing operation from the approach hover point be conducted visually. For the rooftop vertiports, various rules to insure safety in the deck operations will be necessary. It is possible that in very poor visibility conditions that all approaches will be made to one landing pad, and a transfer to an unloading pad made by taxiing on the roof deck. Departures will be made directly from the loading pad along routings separated laterally and vertically from the approach path. To avoid downwash turbulence and minimize heat problems the deck



(A) ROOFTOP VTOL



(B) STOL RUNWAY

FIGURE VIII-4 TAKE-OFF AND LANDING OPERATIONS can be a grill structure with the concrete roof a few feet below. Snow and rain will not collect on the grill surface.

Takeoff Operations

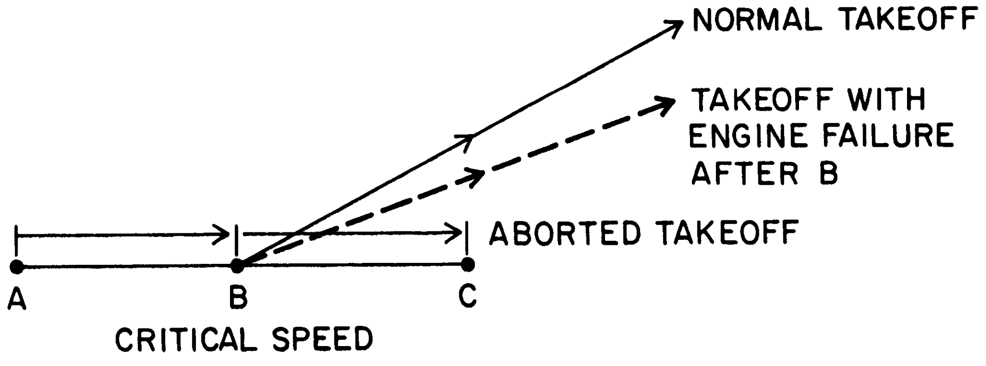
STOL

Two runways will be necessary at STOL terminals to provide the necessary wind coverage for 99.5% reliability in system operation. During low wind conditions, the out of wind runway will be used for crosswind takeoffs to provide increased operations capacity. The landing and takeoff operations are still necessarily coordinated and cannot proceed independently, so that the capacity is not doubled.

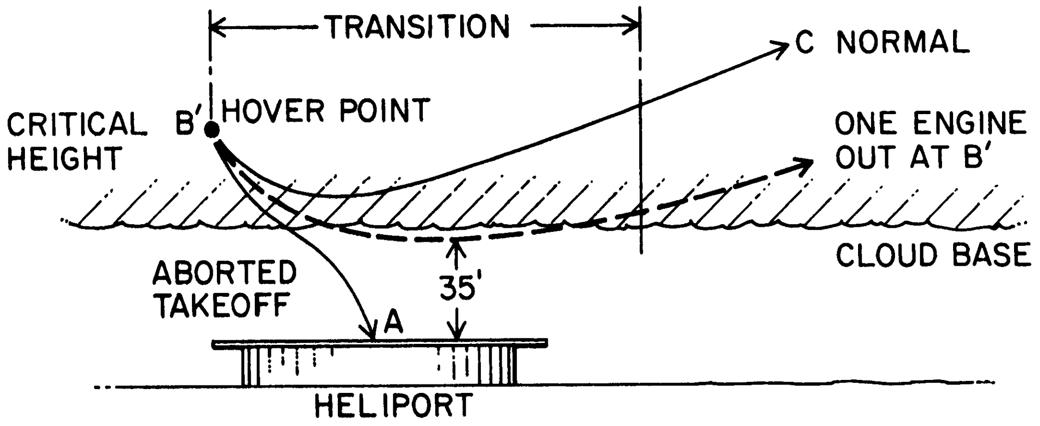
Centerline guidance, a good pilot display, and a takeoff performance monitor will be necessary to handle the engine-out case in 50 feet visual range. An engine failure in the distance AB of Figure VIII-5(A) will cause the takeoff to be discontinued and a stopping maneuver carried out similar to the landing process. An engine failure after B will allow the pilot to retain flying control and climb out along a lesser gradient.

VTOL

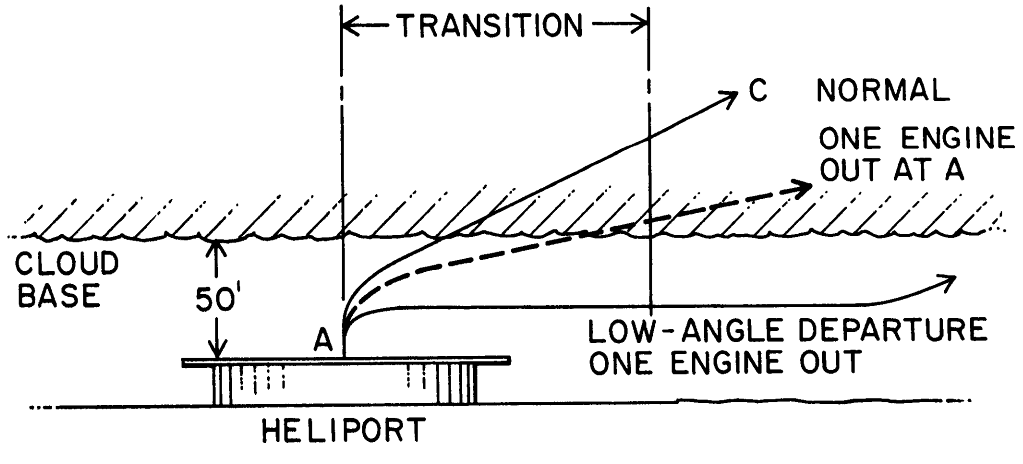
Present VTOL aircraft generally have a critical height similar to the critical speed at point B for the fixed wing aircraft. An



(A) STOL



(B) VTOL - SINGLE ENGINE PROCEDURE



(C) VTOL - MULTI-ENGINE PROCEDURE (ENGINE OUT HOVER CAPABILITY.)

FIGURE VIII-5 ENGINE OUT TAKEOFF PATTERNS engine failure below this height causes a return to the landing pad, while above this height, the takeoff may be continued. The future VTOL vehicles used in this study have been designed to hover safely with one engine-out. This critical height, therefore, disappears for a single engine failure, and the takeoff may be continued at reduced performance from any point. Instead of a backing takeoff path AB'C (Figure VIII-5(B)) to allow a return to the pad, the future VTOL should be able to lift off and climb out along a straight forward path.

This assumes that sufficient low speed control and handling qualities are obtained to provide safe instrument flight during transition in the event of a single engine failure. It also assumes that the probability of a two or more engine failure case is extremely remote (as experienced by present transport aircraft). This latter implies independent operation of individual engines for the VTOL (particularly the jet lift aircraft) to prevent failures caused by failure of a common supply (such as fuel, control system, etc.) or failure of one engine causing multiple failures (such as shedding turbine blades).

For cases where the landing approach is high angle, it may be desirable to perform a low angle departure takeoff as indicated in Figure VIII-5 (C). Here, takeoff transition must be carried out blind at low level similar to the low angle landing transition case.

The Bad Weather Traffic Capacity

Although bad weather conditions will cause IFR operation for less than 10% of the year, it is important from the system reliability point of view that regular service without undue delays be maintained during bad weather conditions. The procedures for organizing the blind flying IFR traffic will necessitate some system slowdown due to extra flying times and distances required (as compared with VFR direct routes), but with proper design, the ATC system can have capacities sufficient to match system demands. The purpose of this section is to review the capacity restrictions which arise in the various components of the terminal area traffic system, and discuss the effect of V/STOL aircraft on these capacities.

The Terminal Area Traffic Sector

To avoid communications congestion in the terminal area, radio messages and instructions can be reduced by using standard arrival and departure routings and specifying ETA's to be maintained to within 0.1 minutes. With groundspeed information and good guidance equipment, aircraft can be expected to conform closely to their planned routings, and avoid the tactical rescheduling process which causes extra messages. With the short haul nature of the trips, and the computer centralized dispatch, reasonable efforts at flow control to avoid peak loading the terminal area traffic system become feasible. In this way, aircraft can be delayed at departure to smooth the arrival flow into the terminal area reducing the requirements for local holding airspace. A procedure for accommodating delays is necessary because of the various unforeseen circumstances which always occur in operational systems. In normal operation, very small delays should be possible by insuring sufficient system capacity.

The Holding Stack

If holding does become necessary in the local area, the vertical laddering process used to maintain safe vertical separation in the holding stack may determine the operational rate (landings per hour) of the traffic system. If we use vertical separation intervals of 500 feet within a stack of five levels and assume a standard 1,000 ft. per minute rate of descent, along with a communications time of 13 seconds, the various stacking models of reference (4) give stacking capacities between 55 and 58 exits per hour.

The Holding Pattern

Both VTOL and STOL aircraft will fly a geographic pattern, while holding, to reduce fuel consumption and noise. The shape and size of the pattern can also be a restrictive element in holding capacity if the random nature of calling for exits from present holding operations is used. However, if we assign scheduled exit times to successive aircraft (which have good guidance systems to make an exit on schedule), the pattern capacity restrictions do not exist. To conserve airspace and provide a simple pattern for automatic equipment, an orbital pattern of a radius equal to 1.5 minutes flying time is assumed.

The Approach Funnel Capacity

With the single ILS instrument runway existing at major airports today, the effect of varying aircraft flying speeds along the common approach glide path forms the bottleneck element to the landing rate, and determines the traffic system capacity. If STOL aircraft have a common approach speed, this capacity will be simply determined by the separation criteria used between aircraft on approach. If the present three mile separation were maintained at an approach speed of 60 knots, there would be three minutes between landings, or a capacity of 20 landings per hour. If longitudinal separations are reduced due to better groundspeed

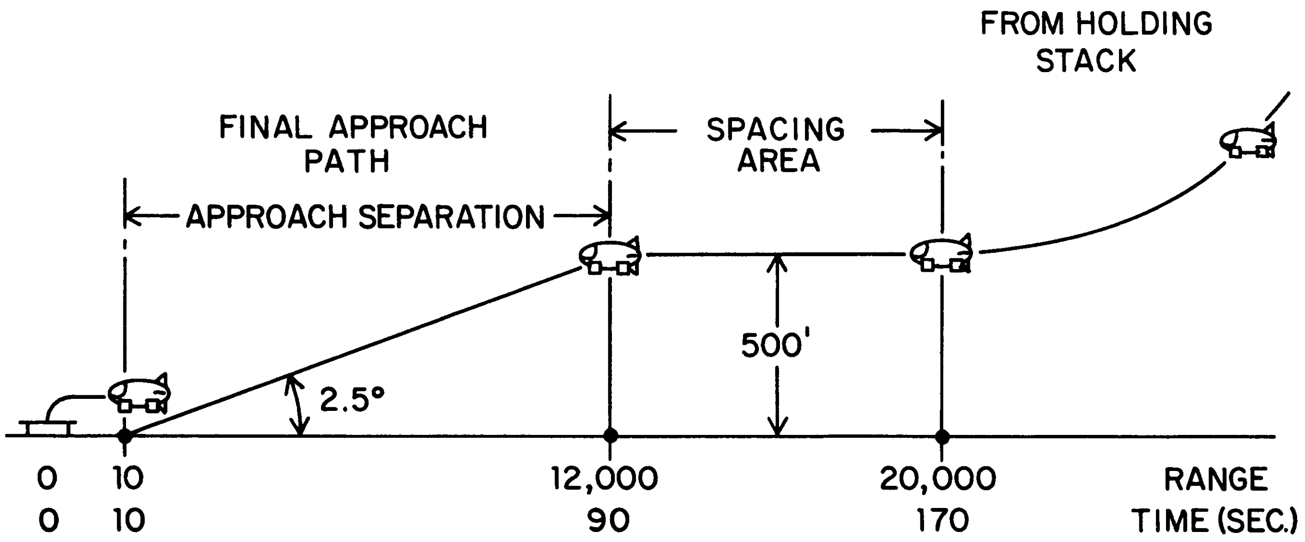


FIG. VIII-6 BAD WEATHER APPROACH AND LANDING PROCEDURE and ETA information, the capacity will be determined by the time separations deemed safe along the approach path. For simplicity, it would likely be the 1.5 minutes duration of the final approach path (see Figure VIII-6) which gives an approach funnel capacity of 45 landings per hour.

Because of the lack of conflicting missed approach procedures for VTOL aircraft and the availability of multiple landing pads, multiple approach paths operating independently are feasible. Thus, using the same funnel separations (Figure VIII-6), the approach capacity may be doubled (or more) above the STOL single approach path procedure. However, for city center sites, approach path obstructions may limit the number of available approach or departure paths.

The Landing Capacity

For an STOL landing in 50 feet visibility on a short runway, the time required for touchdown and rollout will be approximately 60 seconds, or a runway capacity of 60 per hour. For the VTOL the landing pad can be vacated by air or ground taxi in less than 10 seconds, or a pad capacity of 360 per hour. In both these cases, the approach capacity to the runway or pad will govern at 45 landings per hour.

Takeoff and Departure Capacity

For the STOL aircraft, another runway is necessary to intersperse takeoffs and arrivals. The amount of time required for takeoff will only be of the order of 15 seconds, and departure spacing along the departure climb routes, or the interference from landing traffic would determine the takeoff rate. If we assume 1.5 minute departure spacings to match the landing flow and allow insertions of one takeoff after each landing, we have an STOL takeoff capacity of 45 per hour.

The VTOL aircraft will depart directly from the loading pad, and multiple divergent departure paths are feasible. Thus the VTOL takeoff and departure capacity may be many times that of the STOL. Actually, the required takeoff capacity must simply match that of the landing capacity, which will be more likely to govern.

V/STOL VEHICLE SUBSYSTEMS

The requirement for all-weather operations for takeoff and landing, and approach and departure in the IFR terminal area specifies the capabilities of three vahicle subsystems: the stability and control system, the guidance and navigation system, and the anti-weather systems (such as anti-icing, windshield visibility, weather radar). These three subsystems exist in present transport aircraft in varying states of automation and development and the purpose of this section is to outline the requirements for V/STOL vehicles, indicate how these solutions are being obtained, and to reference some of the developments in military and commercial systems which can be expected to be available before 1980.

The Vehicle Control System

The procedures described for all-weather flying require good, low speed control over the vehicle with a positive, fast response to pilot commands and a simple control arrangement for the pilot. Good handling qualities are necessary to insure safe and reliable response to engine failure cases, and permit carrying out the low level transition maneuvers for the VTOL approach and departure.

Control Power Requirements

For all the V/STOL control systems, fast control response at hover or very low speeds will require a method of obtaining control moments using the power of engine either as bleed air ducted to control nozzles, auxiliary control rotor, or through cyclic control over rotor or propeller thrust. Sufficient control power must be available to insure good rate response in roll, pitch, and yaw for the single engine-out case. For those VTOL machines where engine power is used to supply lift, a single control lever should be available to the pilot to control vertical velocity in a simple, straightforward manner. Sufficient engine lift must be available with one engine-out to not only hover, but to supply extra lift for braking powered descents, and providing rapid response in controlling vertical velocity. Provision for this extra power has been allowed for in the vehicle design analyses used in this study.

Good control power and stabilization are both necessary to carry out the transition maneuvers as safely and as quickly as possible in order to reduce fuel consumption and reduce noise production. Providing excess control power for emergency or unusual conditions will not mean it has to be used continuously since good stabilization means small displacements from a desired transition maneuver or approach path.

Vehicle Stabilization Systems

The stabilization system for low speed air vehicles required to do precision instrument flying will necessarily involve automatic equipment. Although control can be maintained by using jet or propeller thrust, the loss of aerodynamic damping due to low air-speeds means that damping must be supplied automatically to insure good handling qualities. By measuring various feedback quantities, the automatic system can be extended to give any desired handling qualities, or the pilot can be given control over a vehicle-control system combination which responds quite differently than the basic vehicle.

The design of VTOL stabilization systems has been progressing for several years and has resulted in several highly successful stability augmentation devices designed primarily to simplify the problem of controlling the attitude of the aircraft. It has become apparent that attitude stabilization is not a sufficient aid to the pilot to permit all-weather IFR operation at close to zero forward speed or in steep descents. An additional degree of stabilization is required in which the stabilization loop is closed around the primary control function involved in these flight regimes, i.e. the positioning of the aircraft in space relative to a fixed point whether on the ground or in a beam.

The flight characteristics of the VTOL aircraft at slow and zero forward speed which necessitate this type of stabilization are not immediately evident. Since the requirement for safe all-weather operation along any flight path, regardless of wind direction, is a predominant requirement for the VTOL systems discussed in this report, it is considered desirable to examine the control factors involved in some detail. The discussion which follows is taken from that contained in reference VIII-8.

Flight Characteristics of VTOL Aircraft

For the past few decades the aerodynamicist has been concerned with designing aircraft such that the inherent stability characteristics as determined by the aerodynamic forces would provide satisfactory handling qualities. It has become increasingly apparent that this problem is one that can no longer be solved by aerodynamic means alone and that additional artificially generated stability characteristics must be provided by electromechanical means. Although this conclusion is far from being universally accepted and is resisted largely because of question as to the reliability and safety of automatic control equipment, the rapidly advancing technology of flight instrumentation justifies greater reliance on automatic control and stability devices. This is true for all the speed regimes, but it is of particular interest to examine its significance in the hover and low speed flight regimes of VTOL aircraft.

Control of an aircraft at zero forward velocity is a fundamentally different problem from control in forward flight. The major difference is a change of reference from attitude variations around a well-defined flight path to changes in position and height above a fixed surface of the earth on which presumably it is intended to effect a landing. Fixed wing aircraft may be readily stabilized about their flight path by the provision of static stability and damping and, where aerodynamic derivatives are insufficient, simple attitude sensing devices can be used to supply the necessary control feedback. The problem of providing suitable handling qualities to a VTOL aircraft is by no means so simple.

The problem arises from the essentially neutral stability characteristics in hovering flight of all VTOL aircraft and the fact that the control of lateral position and horizontal velocity is obtained by inclination of the thrust vector. Safe landing requires zero horizontal velocity at the instant of contact, certainly zero lateral velocity in order to avoid turning the aircraft over and the achievement of this trim condition is by no means a simple process as anyone who has attempted to land a helicopter will recognize. Under gusty conditions, the VTOL landing problem becomes particularly severe.

The nature of the problem may be readily understood if it is realized that the pilot must control two accelerations resulting from his initial control deflection before he achieves the desired horizontal displacement. The following idealized discussion will illustrate this problem.

It is simple to position an object which is held by spring restraints between, say, two points A and B by the application of sufficient force (Figure VIII-7(A)). If the object is held by viscous dampers instead of springs, moving it from one point to another precisely is a more difficult process since the force applied produces a velocity rather than a displacement (Figure VIII-7(B)). If the object has no restraints either spring or viscous but simply mass, positioning it between the two points A and B becomes quite difficult since an applied force produces an acceleration and, upon removal of the force, a velocity is left which requires opposite force to arrest the motion and, hence, a high degree of anticipatory skill (Figure VIII-7(C)). In the case of a hovering VTOL aircraft, the position in space is usually controlled by tilting the aircraft which produces a lateral force proportional to the angle of tilt (Figure VIII-8). The angle results from the application of a control moment by the pilot, but since there is no inherent damping or static stability in pitch or roll the application of the moment produces an angular acceleration and not an angular displacement. The pilot thus has the difficult problem of defining the angle of tilt when the application of his control produces an angular acceleration.

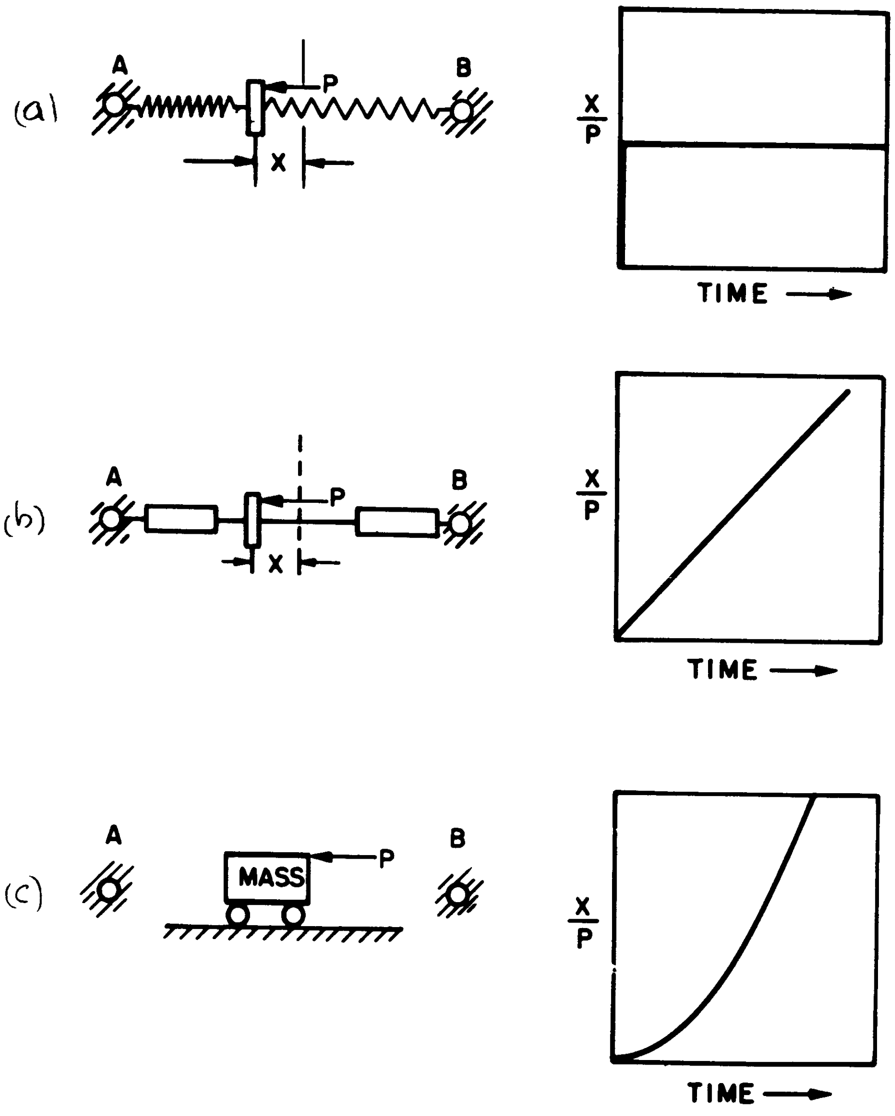
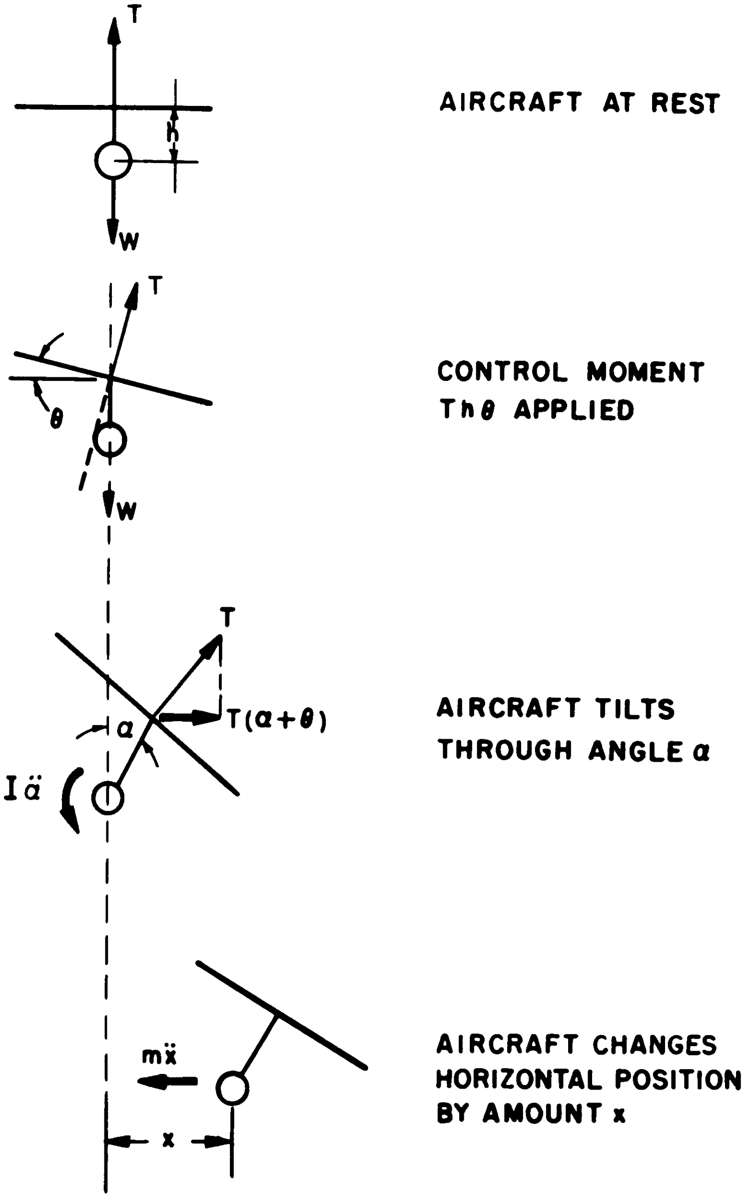


FIGURE VIII-7 - EXPLANATION OF CONTROL RESPONSE PROBLEMS



SIMPLIFIED EQUATIONS OF MOTION $\begin{cases} m\ddot{x} = T(\alpha+\theta) \\ I\ddot{\alpha} = Th\theta \end{cases}$

FIGURE VIII-8

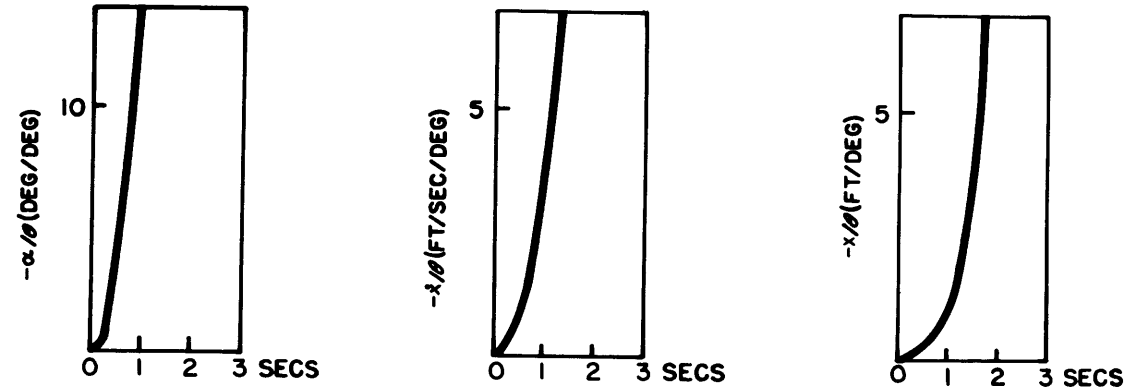
Futhermore, this angle of tilt produces a horizontal acceleration when what is desired is a change in horizontal position. Thus, corrections in horizontal displacement must be achieved by controlling two accelerations, and this is a formidable task.

An experienced helicopter pilot, therefore, uses horizontal tilt for his primary visual cue in controlling horizontal position, thereby eliminating the horizontal inertia lag. Experience and skill allow him to relate subconsciously attitude changes to position changes. Under noncontact conditions, the problem is evidently aggravated and even a highly skilled pilot has difficulty in hovering on instruments. His horizontal position is usually completely undefined relative to the ground and continuously changing in the presence of ambient winds and corrective attitude control inputs.

VTOL Stability Augmentation Systems

In order to alleviate this problem, it is customary to change the angular acceleration response in tilt to an angular displacement response by suitable automatic control equipment operating off gyroscopic sensing devices and this has been done successfully on most current helicopters. However, elimination of the horizontal acceleration response is more difficult and requires the provision of position stabilization equipment sensing horizontal acceleration. Such equipment has been developed for inertial navigation systems to a much higher degree of refinement than is necessary for VTOL stabilization and the applications of these techniques for VTOL stability and control are currently underway (reference VIII-5). The result may well be an order of magnitude improvement in the handling qualities of VTOL aircraft and certainly will permit all-weather operations down to zero visibility conditions with complete safety and without excessive pilot training requirements.

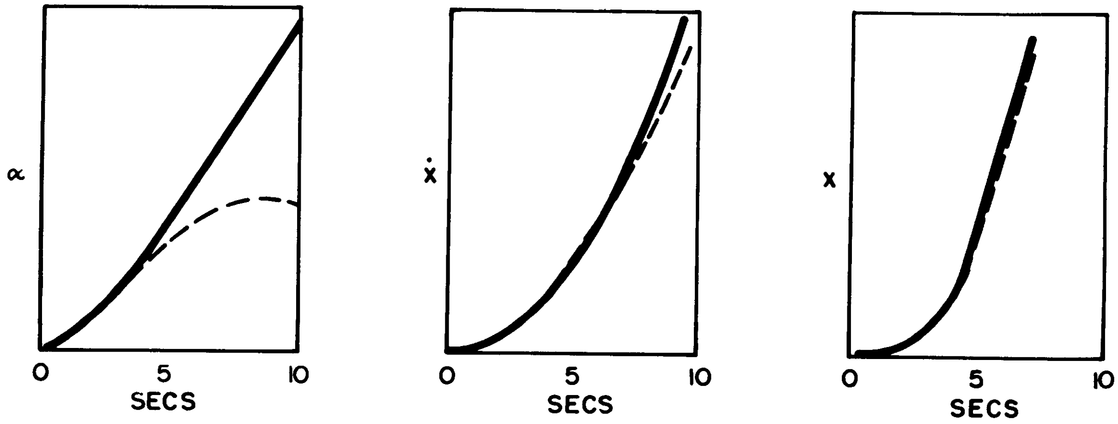
In Figure VIII - 9, comparisons are presented of the position response characteristics for a helicopter with different types of stabilization and using the simplified equations of motion of Figure VIII-8. These response characteristics are typical for all VTOL aircraft. The unstabilized machine (Figure VIII-9(A)) shows the rapid divergent type of response following a step input of control. This divergence is simply the result of controlling through the two second order lags represented by the moments of inertia in pitch and the mass of the aircraft and is not due to the slight inherent oscillatory instability in hovering exhibited by all VTOL aircraft. Figure VIII - 9 (B) shows the response with and without the aerodynamic derivatives included and their effect on the



PITCH ANGLE HORIZONTAL VELOCITY HORIZONTAL DISPLACEMENT

RESPONSE OF TYPICAL UNSTABILIZED HELICOPTER TO STEP CONTROL DISPLACMENT

FIGURE VIII-9(A)



EFFECT OF AERODYNAMIC DERIVATIVES ON RESPONSE OF UNSTABILIZED HELICOPTER TO PULSED CONTROL DISPLACEMENT

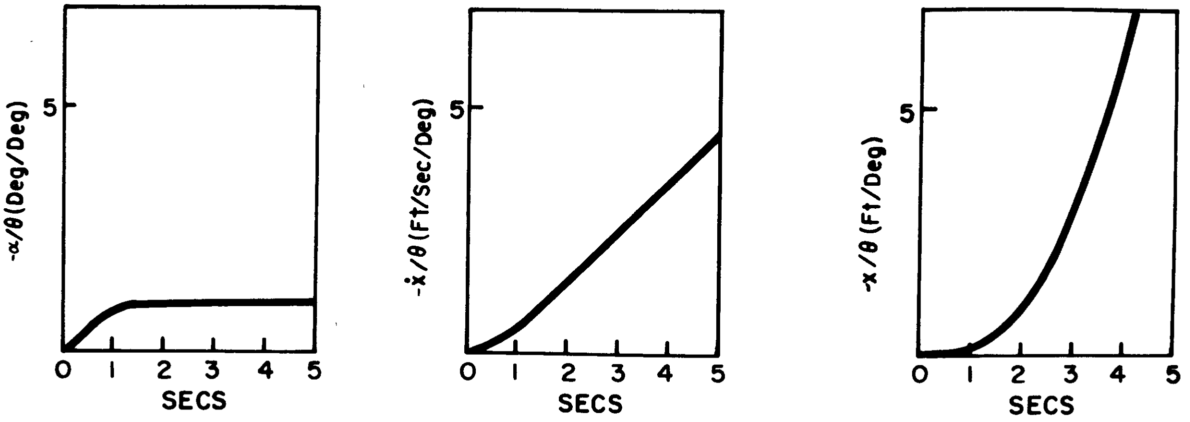
━━━ SIMPLIFIED EQUATIONS

– – – INCLUDING DERIVATIVES

FIGURE VIII-9(B)

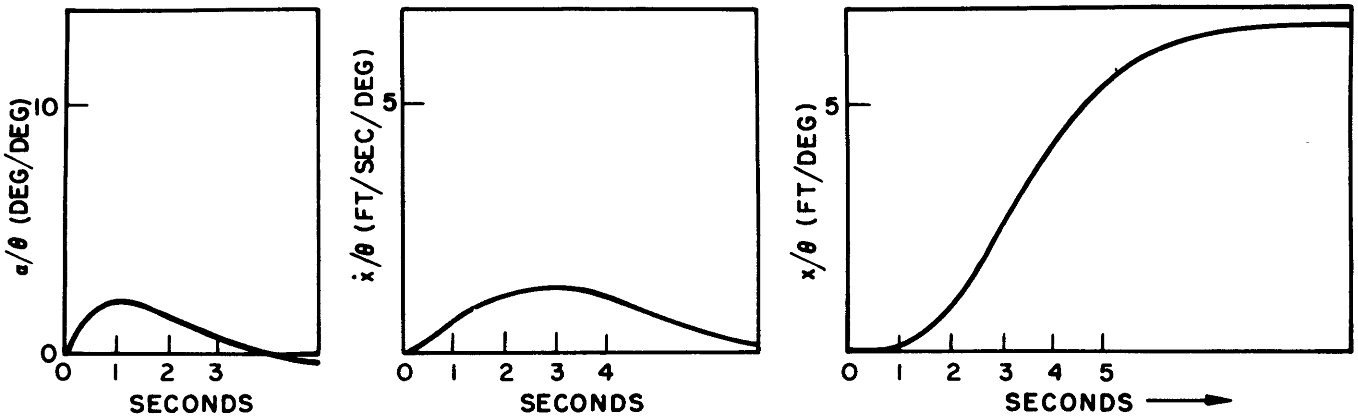
initial response characteristics are evidently small. A small pulse input was used in order to clarify the primary effect of the derivatives in determining the long time response in pitch.

The effect of providing conventional stability augmentation in pitch or roll by attitude and rate of change of attitude feedback is shown in Figure VIII-9(C). The position response remains divergent although somewhat improved since the second order lag due to the moment of inertia in pitch has been modified. Finally, the effect of providing position feedback of the type discussed above is shown in Figure VIII-9(D). Whether it is necessary to go to the extent of providing static position stability, that is, a tendency to return to the initial position following control neutralization, is questionable. As discussed below, it is believed that a horizontal velocity proportional to control displacement would provide close to optimum control characteristics, but it is also believed that positive position stability must be provided in the hands-off condition. This means that the aircraft would respond to a control displacement with a change of horizontal velocity, but that if the pilot neutralizes his controls the aircraft would maintain a position in space regardless of extraneous gust inputs for a period of at least several seconds. It is this feature which would permit the safe approaches under conditions of low visibility in a congested area. As mentioned above, adequate control power must also be provided to



TYPICAL RESPONSE OF HELICOPTER STABILIZED IN PITCH OR ROLL ONLY
STEP DISPLACEMENT OF PILOT'S CONTROL
CONTROL FEED BACK : $\theta_s = k_1\alpha + k_2\dot{\alpha}$

FIGURE VIII-9(C)



TYPICAL RESPONSE OF POSITION STABILIZED HELICOPTER TO STEP INPUT

CONTROL FEEDBACK : $\theta_S = k_1\alpha + k_2\dot{\alpha} + k_3x + k_4\dot{x}$

FIGURE VIII-9(D)

achieve reasonably rapid responses even in the event of engine failure.

The Optimum VTOL Control System

The following discussion is taken from reference VIII-5.

Since, for the displacement control system, the horizontal displacement of the aircraft is directly proportional to the displacement of the pilot's control, it is apparent that for reasonable control sensitivities only a limited maneuvering range is possible. Additionally, a displacement control system has the characteristics of a simple regulator rather than a servo-system. Because of this, a steady control input is required to correct a guidance error. Unless the required control displacement can be accurately estimated, overcontrol is likely since the effect of a control error is not readily estimated until the aircraft has stabilized at the position. In contrast, the velocity control system has unlimited maneuvering range regardless of the control sensitivity, does not require a steady input to correct a guidance error, and the suitability of the initial control input can be estimated by the actual closing rate on the destination. For these reasons, and since the velocity control system does provide neutral position stabilization, the velocity control system is considered to provide the optimum response characteristics.

The practical significance of the improved response characteristics obtainable by the use of a velocity feedback control system is better shown in Figures VIII-10 and VIII-11 which summarize the results obtained from flight control system simulation studies on an analog computer. Figure VIII-10 shows the required pilot's control motions for a simple position change task with an electronic representation of an ideal pilot. The first trace shows the time history of the position change. The remaining traces show the control motions which would be required of an ideal pilot to accomplish this position change using a velocity control system, an attitude control system, and a conventional control system without feedbacks. With the velocity control system, the "pilot" moves his control an amount sufficient to command a velocity appropriate for the distance to be covered, maintains this control displacement during transit, and then neutralizes his control as he nears the destination to come to a stop. If the pilot's initial estimate of the desired velocity is incorrect, a small displacement of his control will directly correct the velocity to that desired.

With the attitude control system, the pilot is required to make two pulse type control motions in order to execute the position change. The pilot must estimate the magnitude and time duration of each of these pulses to achieve the desired results.

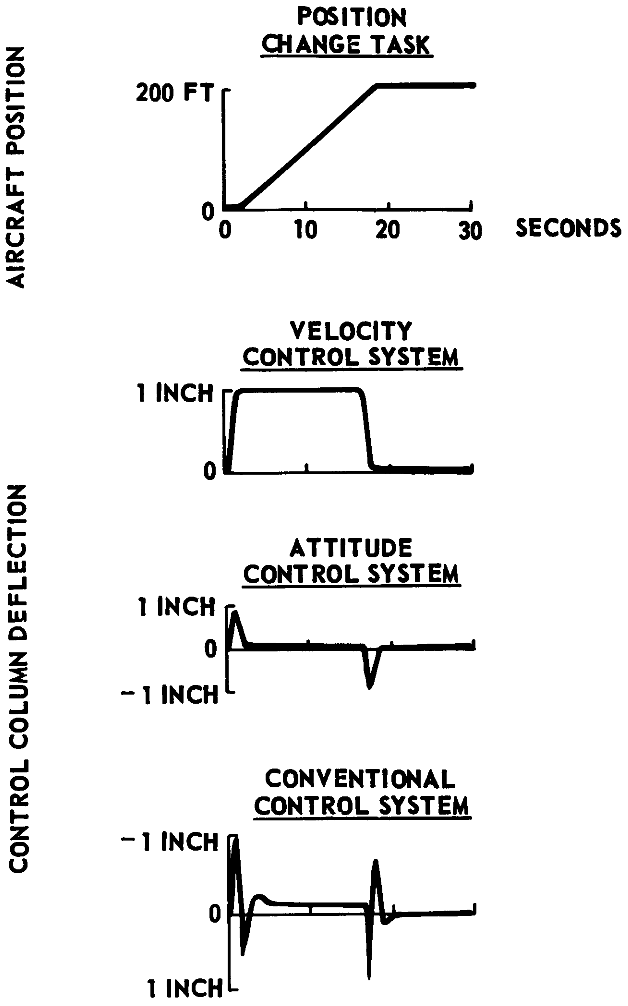


Fig. 2-7. Required control deflection for position change task with ideal pilot.

FIGURE VIII-10

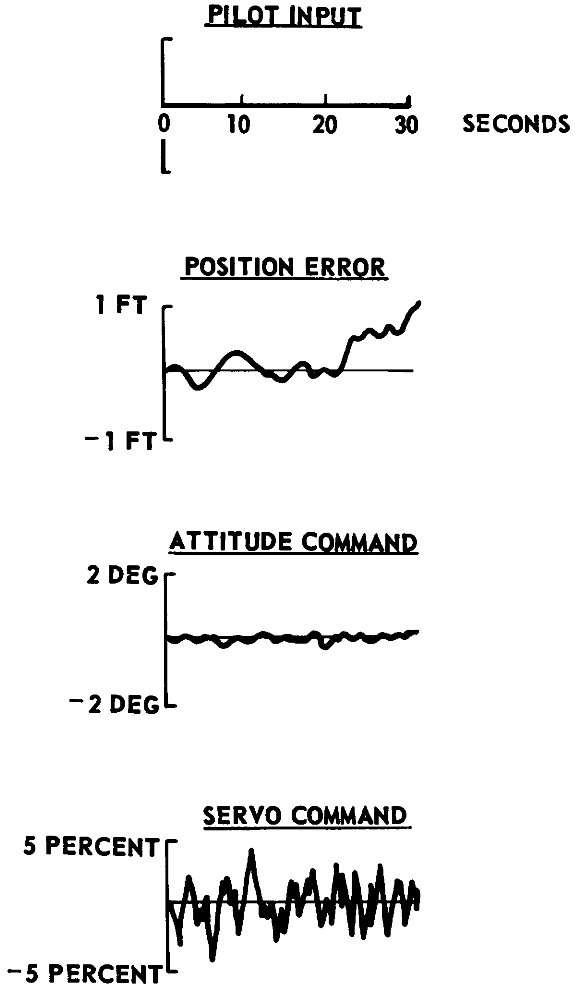


Fig. 2-8. Hovering performance of velocity control system under gust conditions (30 fps peak gusts).

FIGURE VIII-11

If his initial estimate of the commands is incorrect, another pulse, whose magnitude and time duration must be estimated in advance, will be required.

The required control motions for a control system without any stabilization are much more complicated as can be seen from the Figure VIII-10. In the absence of any feedbacks, at least 3 doublet motions are required to perform the position change task. This great increase in the number of control motions required is due entirely to the inability of the control system to provide direct control over the particular aircraft motion required for the tasks.

Figure VIII-11 shows the position stabilizing capabilities of a velocity control system under conditions of fairly severe atmospheric turbulence.The data of this figure was also obtained from analog computer studies, but with the pilot's control fixed at zero displacement. Thus the figure is indicative of the results to be obtained in practice with the pilot not operating his controls. The trace showing the attitude control system commands (the inner loop of the velocity control system) is indicative of the control motions which the pilot would have had to execute with an attitude control system to achieve the same position holding performance. In a similar manner, the trace showing the primary flight control servo commands is indicative of the control motions which the pilot would have to execute with a conventional control system without feedbacks to achieve the same position holding performance. It is quite clear from the figure that the velocity control system can provide a high degree of position stabilization and, in addition, will free the pilot from an otherwise complicated control task and permit him to concentrate most of his attention on the guidance and navigation problems of the mission.

The basic concept of a velocity flight control system for the flight path control in the horizontal plane is shown in Figure VIII-12. As shown in the figure, the signal from the pilot's control is compared with a signal proportional to the velocity of the aircraft with respect to the earth. The difference between the desired and the indicated velocity is then used as a command signal to an attitude control system which controls direction of the thrust vector as necessary to reduce the velocity error to a small value. For use in flight control system (as opposed to a navigation or guidance system), the most desirable reference coordinate frame for the velocity feedback signals appears to be the Earth-aircraft control frame.

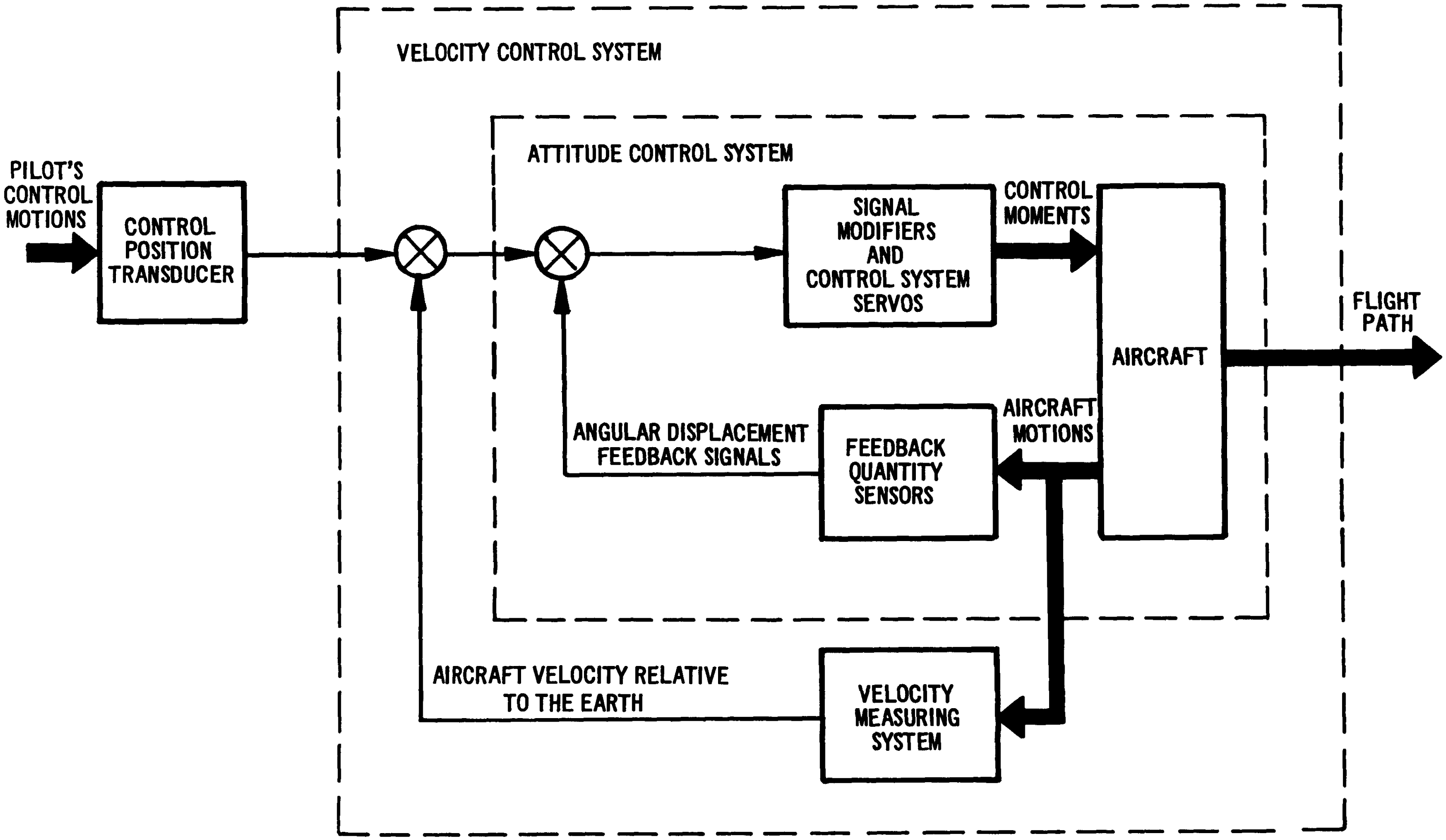


Fig. 2-9. VTOL velocity flight control system for hover and low speed flight (basic concept).

FIGURE VIII-12

As discussed above, a velocity control system for vertical flight path control would control thrust magnitude as necessary to reduce the vertical velocity error to a negligible value. Typical missions place much less emphasis on vertical maneuverability than on maneuverability on the horizontal plane, however. Thus, under practical conditions, it is frequently desirable to operate the aircraft at a fixed altitude, corresponding to a constant indication from a barometric altimeter or at a fixed distance from the ground, corresponding to a constant indication from a terrain clearance indicator such as a radio altimeter. Because of this, it may be desirable to modify the vertical velocity control system to function as a displacement control system by employing a feedback signal from the type of height indicator appropriate to the desired operation.

In order to summarize the ideas contained in the above discussion concisely, consider the problems of stabilizing a hovering jet vehicle about the lateral or rolling axis. (See Figure VIII-13.) The aircraft will be controlled using a variable rolling moment, $M(\ddot{\phi})$, which produces a rolling acceleration response ($\ddot{\phi}$). For a conventional aircraft in steady forward flight, the rolling velocity creates an opposing roll moment, causing the damping of the rolling motion, and effectively

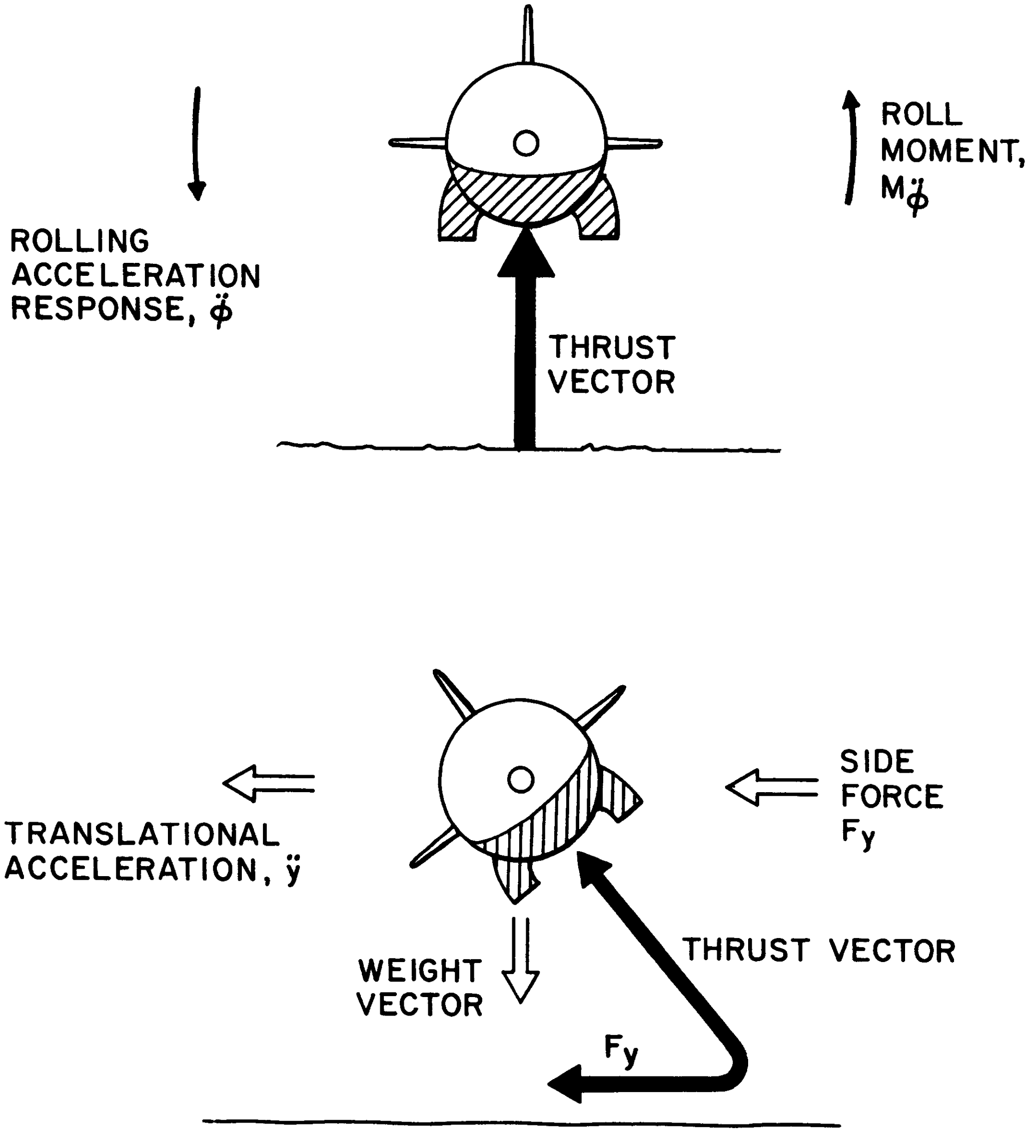


FIG. VIII - 13 HOVERING DYNAMIC STABILITY giving the pilot control over rolling velocity ($\dot{\phi}$) rather than rolling acceleration. In the case of VTOL aircraft, this damping moment does not exist or is negligible unless artificial stabilization is provided. However, by noting the roll angle, the pilot can control the aircraft in either case, although the task is much easier when aerodynamic damping is present.

As the vehicle tilts, a lateral force component in the y direction (Fy) is produced due to inclination of the thrust vector which tilts with the aircraft. This force translates the vehicle sideways, i.e. there is a translational acceleration, ($\ddot{y}$), in response to any roll angle ϕ . Again, as the y velocity builds up, there is an aerodynamic drag force resisting the motion, so that the pilot has control over translational velocity rather than acceleration, but for small displacements around hover, this drag is negligible and there is therefore an acceleration response ($\ddot{y}$) to a given Fy.

Thus, as before, the pilot has two accelerations between his control motion and the y displacement of the vehicle, or he must control a fourth order system, which is almost impossible, even under laboratory conditions with any degree of precision. He, therefore, controls by attitude rather than by position, inferring from the horizon position the lateral or fore and aft displacements of his aircraft. This is a difficult task requiring good visual cues and special training. For blind flying a VTOL machine, exceptionally good instrument displays are necessary to allow the pilot to continue to supply the stabilization and no satisfactory system has yet been developed which would permit blind flying close to hover unless automatic equipment is supplied to provide some damping to partially stabilize the vehicle and ease the pilots' job. This normally is done by measuring tilt rate ($\dot{\phi}$) and using it in a feedback loop to supply at least rate damping and generally in addition an attitude feedback (static stability) in order to give handling qualities similar to the forward flight case. The pilot is now flying a vehicle-control system which has a different response to control inputs.

In newer concepts of VTOL stabilization discussed above, the quantities $\dot{y}$ and $\ddot{y}$ are measured or derived. By this means the complete stabilization of the vehicle-system combination can be obtained and the pilot given control displacements directly proportional to velocity ($\dot{y}$) or position (y). The loop is thus closed around the displacement which it is desired to control and no anticipation or inference on the part of the pilot is required. With these systems, the piloting task is reduced by essentially relieving him of the stabilization and control functions, while retaining his responsibilities in guidance and command functions. The slow flying vehicle can remain on the ground track the pilot selects, or remain hovering, hands off, over a fixed ground point, independent of wind velocities.

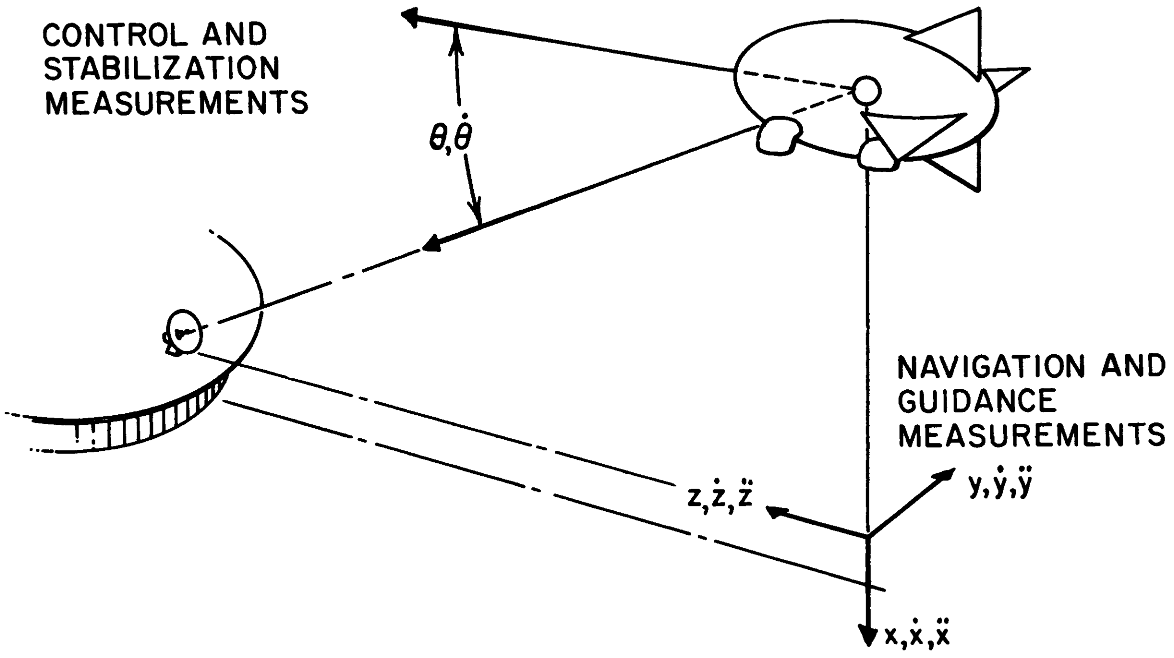
The automatic systems which perform these types of stabilization discussed above are being developed (Ref.VIII-5 and 6) both for VTOL and conventional aircraft. They drastically reduce the problems of instrument flying of air vehicles, relieving the pilot workload at the same time as allowing more accurate conformance of the aircraft to any assigned three dimensional path. This is necessary to provide safe, reliable operation of the V/STOL Air Traffic Control System in the terminal area. Since this reliance is being placed on automatic systems for operations in 1980, the safety aspects demand reliable, tested equipment, and redundant aircraft systems. With the military requirements, and the continuing development of sub-systems, it is certain that commercially acceptable stabilization and control systems would be available for V/STOL air vehicles before 1980.

Vehicle Navigation and Guidance Sub-Systems

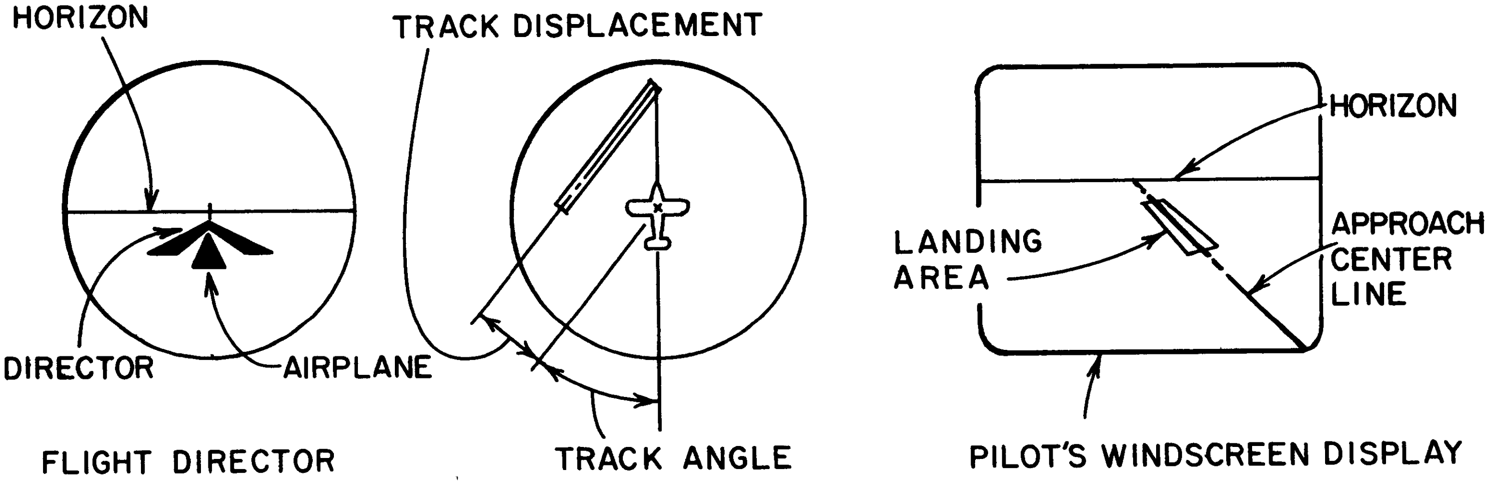
The methods indicated for air traffic control in the terminal area require an accurate and flexible navigation system to define the various three-dimensional arrival and departure routings, and an improved guidance system to provide auto-tracking of these routes, and an analog display for pilot monitoring (or manual guidance) along the assigned routes.

The navigation system should give accurate and continuous information about position in three dimensions (x, y, z) and rate of change of position ($\dot{x},\dot{y},\dot{z}$). The accuracy as previously stated should be of the order of 1,000 feet in the horizontal plane (x,y), and 10 feet in pressure height (h). Coverage should be available at low levels from 500 to 5,000 feet in the terminal area, and preferably should avoid any changes of datum (such as tuning in new radio facilities). For final approach, more rigorous accuracy is required in defining the glide path in (x, y, z) dimensions. A radio navaid which allows increasing accuracy as the landing area is approached, and which can define variable angle glide paths, (and a variable angle localizer for the VTOL multiple approach and departure paths) is desirable.

The guidance system should have available from the navigation system, ground referenced rate of change of position ($\dot{x}$, $\dot{y}$, $\dot{z}$) and accelerations ($\ddot{x}$, $\ddot{y}$, $\ddot{z}$) for use in providing stable, but tight auto-tracking of a specified arrival or departure



(a) NAVIGATION AND GUIDANCE REQUIREMENTS FOR VSTOL TRANSPORTS.



(b) FLIGHT DIRECTOR DISPLAYS

(c) ANALOG THREE-DIMENSIONAL DISPLAYS

FIG. VIII-14

route, and for generating pilot displays as indicated in Figure VIII-14. These pictorial displays are presently being developed for military aircraft and can be displayed on the windscreen to allow superposition on the real world and ease the problem of pilot transition from instrument, blind flight to visual flight for touchdown. Their generation requires information on (xyz, $\dot{x}\dot{y}\dot{z}$, and $\ddot{x}\ddot{y}\ddot{z}$) with excellent dynamic response and low noise content of information.

The flight director displays represent the present guidance instrumentation. Figure VIII-14(b) indicates that local aeronautical charts can be displayed as background to avoid the handling of multiple pieces of paper of varying size which are essential in today's methods of instrument flying. The display of chart information is available commercially at present, and integration with horizontal situation displays will probably occur in the next generation of transport aircraft.

With the availability of $\dot{x}$, the ground referenced longitudinal velocity, it should be feasible to specify a constant groundspeed, or a fixed time of arrival for traffic in the terminal area. This greatly simplifies the problems of spacing arrivals for landing operations. For the pilot, a display of estimated time of arrival at any point should be computed to the nearest 0.1

minutes, and it is feasible that the pilot could command arrival at a given point at a specified time and have automatic equipment provide the necessary guidance. A suitable area for path stretching and groundspeed variation can be set aside previous to starting the final approach. The pilot (or his automatic equipment) will provide the necessary maneuvers in contrast to the radar vectoring procedures of today's terminal area traffic system.

The Anti-Weather Systems

Experience with flying in all types of weather with fixed wing aircraft has led to various successful systems for dealing with the effects of rain, snow, icing, hail, turbulence, etc. on these aircraft. For the various types of VTOL aircraft which can be considered for a 1980 system, many of these solutions can be extended, and probably applied to new problems which may occur.

Icing, in its various forms, has been successfully solved by heating elements, or elastic boots for wing surfaces, by alcohol or heaters on propellers and rotors, and by heaters and drains in jet engine nacelle designs. There is no reason to expect that these solutions are not directly applicable to the advanced helicopters, tilt wings or jet lift aircraft being examined here.

In the Northeast Corridor, heavy snow conditions at low levels can be expected. Similar solutions to any problems arising from wet snow collecting in engine intakes, etc. can be applied from past experience.

Since these aircraft will tend to cruise at lower levels(similar to piston aircraft), it is probable that weather radar will be necessary to avoid passange through thunderstorm cells and the resultant presence of hail. Radar advisory service from the ground may be sufficient to deal with this problem.

Rain presents a problem through a reduction of forward visibility through the windscreen. Windshield wipers have not been an adequate solution, and recent developments have seen methods of ejecting a glycol mixture onto the windscreen which eliminates the effects of high speed rain. Good forward visibility is, thereby, retained during approach to landing in rainstorms.

Vehicle Requirements for a High Capacity IFR System

The previous sections have outlined the operational procedures and requirements for a reliable, all-weather short haul air transport system. It would be best to review those vehicle requirements which differ from the capabilities of today's air vehicles in order to point out the need for further developments.

Auto Stabilization

In order to reduce pilot workloads, and produce good handling qualities, all V/STOL aircraft require some developmental efforts to fully stabilize air vehicles, and change the type of pilot inputs required. Work by NASA, the military, and industry is underway in this area.

Auto Guidance

To allow close conformance of traffic to planned routings in the terminal area, automatic tracking of specified three dimensional paths must be available. This requires better short range navigation systems, and better flight director-autopilot developments. These systems are feasible at present, but there are few working examples and further development is necessary.

Measurement and Use of the Groundspeed

In order to allow the spacing responsibility to be accepted by the pilots, control and measurement of groundspeed must be available, and display of expected and required times of arrival at given points in the terminal area made possible. Much work remains to be done before experimental models of such guidance systems are available.

Commonality of Approach Speed

To ease the timing and spacing problems, it is justifiable to request a fixed, common airspeed on final approach. This may be difficult with a variety of STOL aircraft unless a higher speed is chosen, but VTOL types, with the high angle powered approach, may easily conform to a common approach speed over a variation in size and type of vehicle.

Good Handling Qualities at Approach and Transition

With automatic stabilization, good handling qualities as seen by the pilot can be insured as long as the basic aircraft has sufficient control power. The design of the automatic equipment is much eased if the basic aircraft does not have any unusual effects due to power, wind effects, transition maneuver, loss of control effectiveness, downwash, etc. The extensive V/STOL prototype aircraft programs should contribute much flying experience to this problem.

Noise on Approach and Departure

Since these aircraft are expected to operate within the city center (and, more to the point, in suburban areas), objections may be expected from local populations in the vicinity of the terminals. The characteristics and sound levels of the noise generated during takeoff, landing, departure, and approach are, therefore, of great interest. While much can be done in selecting suitable landing sites, the lowest noise level achievable will mean more widespread acceptance and operation. Much work remains to be done in producing quiet production of thrust and power for these vehicles.

Freedom from Weather Effects

The transportation system requirements for reliability are such that no disturbance due to any sort of weather, short of a hurricane, can be tolerated. There may be some weather effects discovered in operating V/STOL vehicles in all types of weather, but the fixed wing experience should contribute greatly to their solution.

The Application of Inertial Guidance Technology To the Airbus System

The systems which have been developed for submarine, missile, and aircraft guidance using a stabilized platform to measure position, velocity, and acceleration relative to inertial or geographic space find another suitable application to the short haul Airbus system. The platform does measure $(y, \dot{y}, \ddot{y})$ and the angular information $(\Phi, \dot{\Phi}, \ddot{\Phi})$ with good accuracy and good dynamic characteristics. It does provide suitable information for automatic velocity or position stabilization, and for generating advanced guidance displays of various descriptions. As well, it will provide navigation information of extreme accuracy over the short flight times involved in the Airbus system.

Such systems have been proposed for the supersonic transport, and are presently being tested by major airlines. Their continuing development and airline acceptance of their capabilities for guidance and stabilization, as well as navigation is insured. Direct application to military helicopter and V/STOL aircraft for weapons system purposes is being made, and will continue to provide a basis for advanced commercial VTOL systems.

Conclusions

The serious air traffic problems of fixed wing traffic will cause extremely severe delays by 1980 unless more ILS instrument runways can be placed in operation within the Northeast Corridor. The VTOL Airbus system can alleviate present airport congestion by allowing the distribution of short haul air terminals within city center and suburban areas, thereby reducing the short haul traffic at the Corridor airports.

The VTOL aircraft will have advanced automatic control, stabilization, guidance and navigation systems available by 1980. These systems will allow multiple access paths, simultaneous landing and takeoff operations at VTOL terminals. The high operational capacity and ability to distribute terminals will eliminate any sizable traffic delays in the Airbus system.

The Airbus system will be much more operationally reliable than present air systems. Completion factors better than 99.5% can be expected,with only winds of hurricane force and very dense snow or fog preventing regular operations on schedule.

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