TURBOFAN COMMUTER AIRCRAFT PROJECT DESIGN STUDIES

by

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DECLARATION

This thesis is the outcome of the research carried out by the author in the Department of Transport Technology, University of Technology, Loughborough. It represents the independent work of the author. Work of other researchers has been referenced where appropriate.

The author also certifies that neither the thesis nor the original work contained herein has been submitted to any other institution for the award of a degree.

L.R.Jenkinson.

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"As a teacher so shall you learn"

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ABSTRACT

Designing successful commercial aircraft is a difficult business; the stakes are high and the risks numerous. Researchers in the past have developed methods that assist the designers in reducing these risks. In recent years such methods have benefited from improvements in computer technology. The work described in this thesis extends these methods to the design of commuter aircraft. These aircraft are more sensitive to operational requirements than other types due in part to their high zero-fuel mass ratio. It is essential that, for such aircraft, the best information possible is available to the designers. The identification of the optimum aircraft configuration and mission characteristics constitutes a vital part of this knowledge.

A review of literature, involving both modern computer-based and traditional search methods, has shown continuing interest in aircraft project design methods from the earliest times to the latest conference. The work presented in this thesis is seen to compliment this interest in computer methods and to apply these techniques to the relatively neglected area of commuter aircraft design.

A survey of commuter operation and aircraft types revealed the often conflicting requirements and regulations which govern the design process in this area. Detailed statistical analysis on a collection of commuter aircraft showed no consistent data patterns, but did indicate the bouyant state of the market.

Earlier research work on the design of twin-engined turbo-prop aircraft had provided some experience in the design of short-haul aircraft. The new work improves these methods and applies them to larger and faster turbo-fan commuter aircraft. Since the turbo-prop work, the optimiser developed at RAE (Farnborough) has been rewritten to work more efficiently and allow larger problems to be tackled. This new optimiser is linked to a new synthesis routine which simulates turbo-fan aircraft design. The synthesis program was calibrated against industrial design calculations and shown to give acceptably accuracte predictions. The resulting design program is fully described and computer listings are presented.

To illustrate the use of the optimisation methods in the devleopment of a new aircraft, a series of industrially related design studies is presented. These studies range from the selection of the initial baseline configuration, through various parameters sensitivity investigations, to the evaluation of aircraft and engine stretch options.

To demonstrate more general types of design study, a series of optimisations in which the engine size is variable was conducted. This provides the designer with a knowledge of the absolute (optimum) design surface and allows him to judge the 'penalties' inherent in his chosen configuration.

The main criticism of optimisation methods lies in the fact that the designer is seldom only interested in the optimum point design. He needs to know what flexibility there is in the choice of configuration away from the optimum so that non-quantifiable influences on the design specification may be considered. The design program developed here has been extended to offer the option of showing the (approximate) shape of the design surface around the optimum point. This type of plot provides a measure of the sensitivity of the design variables in this region, around the optimum point and the location and nature of the constraint boundaries.

The thesis concludes with a discussion on the merits of optimisation studies and offers some suggestions for changes to the design optimisation strategies adopted. These involve non-gradient search methods and lead to recommendations for further research work to develop such methods into useful design tools.

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Chapter 1

INTRODUCTION

1.1 Preview

Although the term 'commuter aircraft' is widely used in the literature to describe aircraft operated by regional airlines, there is no exact definition of the aircraft design classification. In the broadest definition, the term refers to all commercial aircraft from the light/general aircraft class to large aircraft used by smaller airlines on short-haul schedules. This categorisation is now becoming blurred as several of the major trunk airlines are forming close operational links with the regionals and using even larger aircraft types on some of the high density 'spokes' to the central 'hub' airports.

The size of aircraft in the commuter classification is considered to extend over the range from about ten to one hundred seats with range between 200 to 1000 miles. In general, the longer ranges are associated with the larger aircraft but historical trends show that all aircraft are required to fly an increased range as the market for regional networks expands. The current longer range and larger aircraft specifications would have been associated with the major carriers only a few years ago. There are no fundamental difficulties in designing aircraft over such a wide spectrum of size, but several operational requirements intrude on the design specification. For example, aircraft designed to carry nineteen passengers or less are allowed to operate with lower equipment standards by some regulatory bodies. They are also allowed to operate without a cabin attendant (the second flight crew member attending to passenger services). As another example, aircraft designed to carry less than seventy passengers are excluded from some of the mandatory controls of European Bilateral agreements and can therefore freely operate on inter-regional routes. These two considerations are sometimes used to narrow the definition of commuter aircraft to the 19-70 seat range.

The difficulty of linking the definition of classification to regulatory aspects lies in the strong possibility that legislation will suddenly be changed. Already the airworthiness authorities are attempting to alter the 19 seat rule down to 15 seats for pressurised (i.e. more sophisticated) aircraft. It is also anticipated that, with the relaxation of air traffic regulations associated with the introduction of the EEC Single Market Act, manufacturers are looking for the 70 seat limit to be raised to 100 seats. They argue that this will stimulate traffic on the inter-regional trans-state secondary routes (e.g. Bordeaux to Dusseldorf).

In the USA, which is the largest market for commuter aircraft, the 70 seat restriction does not apply but air traffic regulations at busy airports impose a 55 seat restriction for scheduled slots. British Aerospace have recently applied for relaxation of this rule to allow their 64/68 seat ATP aircraft to benefit from the more flexible regional traffic schedules - again illustrating the danger of linking aircraft classification to regulations.

The main investigations in this thesis are directed at the upper band of the 19-70 seat range. Due to interest in the busier routes, which are better suited to the fan-jet designs, the upper limit is extended to the 80 seat size. In reviewing existing and projected aircraft, the full 10 to 100 seat classification has been considered.

1.2 Scope of the Study

The subject of this thesis relates to the efficient design of fan-jet powered commuter aircraft. The need to determine mission and aircraft characteristics which produce the best design stems from the requirement to select a design point for the aircraft which will satisfy a broad market. It is necessary to determine not only optimum designs but also to understand the sensitivity of the aircraft parameters at the selected point.

The choice of mission and aircraft characteristics to achieve a specified objective is likely to be infinite providing the constraints imposed on the problem area are not too constricting. Selection and definition of the best set of values for the aircraft variables will depend upon the model used to define the aircraft design, the techniques used to search for a feasible design, the tolerance imposed on the acceptability of the search, and the criteria used for overall judgement. There are many 'optimum' designs depending on the choice of these problem parameters.

This study will develop methods that will allow such investigations in the design of fan-jet commuter aircraft. These methods will then be used to describe aircraft of various design characteristics.

1.3 Description of aircraft project design

In lecture notes from Boeing, and at an AGARD conference, Wallace(1) describes the three aspects that are necessary for accomplishing a new aircraft design and its full validation. These can be summarised as the definition of the **mission** that the aircraft must accomplish (the primary and secondary objectives of the design process), the definition of the **configuration** of the aircraft to achieve the objectives, and the evaluation of the **economic sensibility** (the primary motivation). Although these aspects are defined here as separate entities, they are recognised as being highly interdependant and only considered so as a convenient simplification to assist in the understanding of the total design task.

Since Wallace's paper in 1972 a further topic has become influential. This involves the environmental, social and political impact of the design and operation. Noise and emission regulations have imposed technical constraints which are now commonplace. Land-use and air congestion are potentially more difficult technical and organisational problems to be considered. The ever-increasing multi-national nature of aeronautics and the associated political and commercial aspects are new and continuous considerations of the design.

The study of each of these aspects is complicated by the extended timescale over which the aircraft design will be utilised and assessed. The changing needs and expectations of the customer will require anticipation if the design objectives are to be wisely prescribed. The introduction of new technologies and the ever changing design and operational regulations will affect the definition of the aircraft configuration. The variable nature of the economic environment will complicate the assessment of the viability of the project. Uncertainties in all these areas makes the validation of the projected design potentially unreliable. To reduce some of the risk it is essential to understand how a specified design will be affected by such changes and to select a configuration which is seen to be less sensitive to the most likely effects.

To assess the design, it is beneficial to use optimisation methods coupled with parametric studies. In this way the design surface around the optimum can be understood and a design point near the optimum selected which suits anticipated developments in the design specification. Since the analysis methods are dependent upon the type of aircraft to be studied it is necessary to develop and validate such methods for each aircraft classification (and possibly size).

1.4 Insufficiency of knowledge

There is no intrinsic difficulty in designing aircraft of the commuter type and many well established methods exist to provide feasible designs. Over the recent past, the introduction of computer methods has made a substantial impact on the initial project design area. The increase in speed of analysis has allowed many more possible configurations to be assessed and as the power available from the computer increases the aircraft design problems can be increased in sophistication (and hopefully accuracy). Computer-based methods are now the accepted form of analysis in the field. The difficulty in using these methods for a particular type of aircraft design lies in the inaccuracy of a generalised method. Each aircraft classification requires a specific computer program to be developed which reflects the idiosyncrasies of the design and its constraints. Such programs have been developed for various aircraft types. For example, at Loughborough[2] the design of twin-engined, turbo-prop, short-haul aircraft in the 12 to 40 seat size was studied using these methods in the mid-1980's.

Since interest in fan-jet commuter aircraft has only recently been renewed, modern methods of anlaysis are not available for this type of aircraft. The methodology developed in the earlier turbo-prop. studies forms a useful basis for the development of such new programs. Using this approach has the advantage that the expertise gained in the earlier work is transferred to the new studies and a higher degree of confidence in the estimating methods can be expected. A review of published literature shows that although there is considerable interest in the general study of commuter aircraft no other work is available which provides methods of in-depth study of the fan-jet type.

1.5 Research Objectives

The main objective of conducting this research is to understand more fully the fundamental nature of the design of fan-jet commuter aircraft. This broad objective is realised by undertaking the following tasks in combination:-

1. To develop methods for the determination of optimum aircraft configurations.
2. To apply the developed optimisation methods to the design of a range of aircraft specifications.
3. To show the trade-off between competing design characteristics and operational parameters on the optimum aircraft configurations.
4. To investigate the sensitivity of aircraft design to changes in problem variables, constraints and objective functions.
5. To illustrate how these methods are used in the preliminary aircraft design phase.
6. To develop methods for the investigation of the design-surface near the optimum point.
7. To apply the methods developed above to show the near optimum sensitivity of the principal design parameters.

1.6 Structure of the thesis

The remaining part of this thesis is divided into four separate sections:-

1. Chapter 2 describes the previously published literature in the field and draws together the various lines of research conducted to show the significance of this new work.

2. Chapter 3 provides some background for the design of commuter aircraft. It outlines the operational factors that are considered as significant and lists technical data on existing and projected aircraft in the commuter market.
3. Chapter 4 describes in detail the optimisation, aircraft synthesis and design surface methods used in the program.
4. Chapter 5 contains a detailed description of each of the aircraft design studies undertaken.

The thesis concludes with a discussion on the methods used, drawing some main conclusions from the work. Finally suggestions are made for extension to the study for future researchers.

Each chapter is 'self-contained'. All publications (etc) referenced in the text are listed after the written part. All figures referred to in the text are placed in numerical order after the reference list

Six appendices, placed at the end of the thesis, contain detailed information to support the main text. Appendix A includes the complete listing from the computer literature search. Appendices B holds the detailed data used in the aircraft survey of chapter 3. Appendix C includes the formula and design relationships used in the design synthesis program. The tabulated results from the various optimisation studies are included in appendix D. A review of the synthesis program is given in appendix E and specimen input and output files are shown in appendix F.

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Chapter 2

REVIEW OF LITERATURE

2.1 Literature search methods

It is always difficult to know how far back to start a literature review, particularly in a field like aircraft design which has so many inter-related and significant lines of development. Fortunately, both methods of search employed in this study identified acceptable starting points.

The traditional method of search, involving the review of inter-referenced papers identified Ivan Driggs (1) lecture to the Royal Aeronautical Society in October 1949. This definitive description of early design methods included the first account of simple mechanisms to assist the design process.

The traditional literature search was reinforced by a computer search using the new ESA-QUEST library system. The NASA file in this system contains all STAR and IAA abstracts back to 1962. This date was regarded as sufficiently historical to support the manual search.

The computer search was conducted in August 1989 and consisted of the following keyword search strategies:-

(a) using *Aircraft* and *Design*, yielded 12731 references.

(b) using *Optimisation* yielded even more references at 31201

(c) combining these two lists gave 863 references

(d) to narrow-down the search area file (c) was combined with *short-haul aircraft* or *commuter aircraft* to show 39 references. These were reviewed in detailed abstract form from the computer print-out.

(e) to check the above list the search was started using a different route. *Airline operations* showed 3475 references.

(f) to narrow-down file (e), it was combined with *short-haul aircraft* or *commuter aircraft* giving 147 references. All these were reviewed by title and 57 manually selected for full abstracting.

For completeness the author/title references of both the above computer searches are reproduced in Appendix A.

It is interesting to note that although the computer search found some extra references it failed to identify several of the important papers found by the traditional search. It is concluded from this experience that, at present, the modern computer library search methods, although useful in providing support search facility, do not offer a complete alternative to the traditional manual search.

The review below combines the significant contributions from researchers in the field found by both search methods.

2.2 Review of literature on aircraft design and optimisation

As mentioned above, Driggs[1] described preliminary aircraft design methods used in the early 50's. These were largely based on systematic graphical techniques involving much empirical data collected from recent past designs. The need of his department, to produce results on new (projected) aircraft design quickly (*"within two or three weeks")* forced the development of fast estimation procedures which *"rationalise and express all the factors which pertain to the art of aircraft design in their proper relationships"* and *".....lead directly to a better understanding of any given problem and therefore assists the designer in arriving at intelligent courses of action"*. These are sentiments close to the heart of all aircraft project designers today. His work preceded the development of electronic computerised methods, so were largely based on the use of mechanical graphical methods including specially prepared slide-rules, nomographs and overlay methods. The need for rapid evaluation of aircraft configuration has been the driving force in many of the methods that followed.

Many researchers attempted to develop methods for the determinaton of optimum planforms in the early years. For aircraft with long cruise segments (large military aircraft and early civil transports) the problem was somewhat simplified but the variety of planform shapes considered at the time made the analysis more difficult. The paper by Sanders[2] is typical of the methods used for the design of the Vulcan B1 and the Boeing B-47 aircraft. At about the same time Legg[3] was reporting on the design of aircraft in Brazil and showing methods of optimum design based on zero-fuel weight fraction for jet and propeller executive aircraft. These aircraft are the predecessors of the successful commuter aircraft currently sold by Embrear. It is interesting to note that the aircraft configurations are similar to modern project designs. Legg anticipated the current trend by observing *"During subsequent investigations the possibility of a better compromise aircraft became apparent...this derived from the use of a small fan engine with very high by-pass ratio, this being in effect the intermediary between turbo-prop and pure jet"*. This is one of the earliest descriptions of the specification of modern commuter designs although Legg was concerned with smaller aircraft at the time and no indication was given of the generality of his statement.

Many researchers, of whom Kuchemann[4] is perhaps the most significant, were attempting to determine pure mathematical procedures for the optimum design of aircraft. In his now classical work, he developed a full analytical treatment for the estimation of aircraft performance over a wide range of speeds. At the time (early

sixties), much of the work of RAE was directed to supersonic and hypersonic aircraft analysis but for completeness he included *"classical and swept wing aircraft"* which we would equate to present day transport aircraft configurations (including commuter types). The brief conclusion to the collected work contains the following passage which over twenty years later could be used as a full justification for this thesis. Speaking of the aircraft design task he says:-
"...even in the solution of partial problems, a very large number of parameters and variables is likely to be involved. In such a situation, and even if all the elements were sufficiently well known, the question arises of how to find one's way to a reasonably good overall solution, if not to the overall optimum. This presents a considerable problem in itself and requires the establishment of new procedures, considerably more complex and powerful than the elementary procedures discussed in this paper. In the past, aircraft have often been built on incomplete knowledge and the viable ones have been selected from the failures in an evolutionary process. This approach is no longer open to us; the costs involved alone forbid this. It appears necessary, therefore, to consider seriously the problem of what strategy should be employed to find the promising solution beforehand......... One aim of the future work, therefore, should be to establish a conceptual framework of the physical processes and phenomena involved and to gain an understanding which is sufficient to recognize all the big trends."

Most of the work on aircraft performance optimisation has concentrated on particular segments of the aircraft trajectory. Schultz[5] in his development of 'calculus of variation methods' showed how Rutowski considered minimum-time and minimum-fuel climb performance. Time-to-climb methods were developed by several other researchers in the late fifties. The 'minimum-fuel-for-cruise' problem was also considered at this time and involved subtle manipulation of the Béguet range formulae. Around the same period, the trajectory was analysed by applying mathematical optimisation principles to the energy state equations. These methods showed useful results for highly manoeuvreable aircraft but were too inaccurate for the simple prediction of transport aircraft performance. Schultz indicated how these methods gave curious results for partial throttle conditions.

With good fortune, the need to develop more complex and powerful methods observed by Kuchemann coincided with the introduction of modern electronic computers and associated numerical methods. This offered the aircraft designer the possibility of considering the total aircraft optimisation problem. In the early days, the computer power available was still insufficient and much effort was directed into efficient packaging of the aircraft problem to suit this limitation. In the late sixties and early seventies several descriptions of how computers were being used in aircraft design were published. Lee[6] described the concept and philosophy of the computerised aircraft synthesis program (SYNAC) developed by General Dynamics. The organisation of the program into discrete modules (input, configuration, geometry, weight, propulsion, aerodynamics and performance) has stood the test of time and is still the basis of most modern program structures. With reported computation times of one minute per aircraft design cycle the results must have been crude. Later developments of the system were anticipated that improved this by an order of magnitude. (Our current programs run 50 times faster than this.)

At Lockheed Georgia[7] a broader approach was developed involving the use of computer graphics and interactive user interfaces. Their program for computer-aided aircraft design (CAAD) was started in 1966 and derivative versions are still used today. The computer interface developed in this work formed the backbone to their separate computer drawing systems which are now widely used in aircraft drawing offices. The paper shows crude, (by present day standards), graphical descriptions of the aircraft and some of its component parts. The linking of these with analytical project design methods was relatively ineffective and must have slowed down the running time of the aircraft design routines. Nevertheless, the concept of a graphical interface to the aircraft design system is shown to be basically sound and still represents an ideal requirement for todays programs.

At Boeing and in Britain (RAE) the interest centered on the development of optimisation methods involving multivariate search techniques. Stepniewski[8] of Boeing described the automated engineering and scientific optimisation program (AESOP). They recognised the need to match search methods with the type of design surface expected. The increasing use of computer methods stimulated the development of many new mathematical algorithms (Stepniewski quotes ten new textbooks on optimisation methods published in the early seventies). The Boeing program incorporated many separate optimising techniques and used automatic selection strategies to choose the best method. The procedures are shown in the paper to be extremely powerful over a wide range of problems. The author concludes by observing that *"The most valuable product of an optimisation study is often the insight resulting from an associated sensitivity analysis"* again reinforcing one of the research objectives of this thesis.

The mathematics department at RAE, in conjunction with the aerodynamics project section, considered the multivariate search technique from a fundamental standpoint. They developed new techniques and incorporated existing methods to build a new optmisation program aimed mainly at the aircraft design and analysis area. The early version of the Farnborough multivariate optimisation program (MVO) were described in detail [9] [10] but it was not until the paper by Kirkpatrick and Larcombe[11] that the full potential for the method was realised. They applied the MVO program to the optimum design of large civil transport aircraft and showed the trade-off between optimum configurations. With success in the civil field they then applied the method to military aircraft but due to the lack of a suitable optimising function this was regarded as less effective. The work highlighted the need for careful management of the basic aircraft estimating methods, the significance of accuracy in these methods and the need to specify design objectives clearly and in a quantifiable form. An attempt to resolve the difficulty of identifying suitable optimisation criterion for military aircraft was described by Huff(12) of Vought. This military aircraft synthesis and analysis program (ASAP) was linked to an air combat simulator. This combination allowed direct comparison of aircraft configurational choices with the degree of flight/control difficulty experienced by the pilot. Such methods would be considered as too extreme for civil aircraft because the design criteria for such a[16] aircraft are much simpler to define than for military types.

Many of the papers described the disadvantages of using optimisation techniques over traditional methods. The need to have parametric study methods available was raised by Wallace(13) in his excellent lecture describing parametric and optimisation techniques and how both integrate with the total aircraft design method. As the number of independent variables increases, the design task falls beyond the scope of parametric study. Conversely, as the problem becomes more automated, so the designer has less influence on the direction of the study. He ended his lecture with the observation that parametric and optimisation techniques enhanced by modern high-speed large-capacity computers makes the design process possible as a truly interdisciplinary design effort. A visionary comment in 1971, anticipating the knowledge-based systems that are currently being developed.

The study of computer-aided methods for commuter aircraft can be traced to Galloway(14), Erzberger(15) and Roskam(16). This last report is useful for the analysis of fuselage configuration but does not tackle the full optimisation problem. The earlier reports deal with smaller size aircraft. It is interesting to note that at this time not everybody considered optimisation a valuable activity; Stengel(17), after studying the effects of fuel conservation on the C141A military transport aircraft concluded that "*the key to fuel minimisation is to make fuel savings the natural way....... to fly the airplane carefully*"

In Europe, Howe(18) described various methods of computer use in the project design process. He showed the inter-relationship between the different phases of the design method and concluded that computer techniques enable a much wider range of designs to be investigated but observed the difficulty of interfacing to obtain the best balance between computer and designer roles. Torenbeek(19) attempted to define design merit functions and showed how various elements in aircraft project design are common to different systems. At the same AGARD conference, the development of the earlier RAE work was described by Edwards[20]. This paper is significant in that, for the first time, a researcher used MVO methods to gain an insight into the basic aircraft model. His discussion on model accuracy and the use of optimisation methods to show the design surface sensitivities are significant and introduced a new aspect to aircraft optimisation studies.

By the early 80's the use of optimisation methods was directed at the assessment of new technologies for commuter aircraft. Galloway[21] and Williams[22] at NASA-Ames and Matsuyama[23] at USAF Academy showed how standardised design techniques could be applied to provide relative assessments of various advanced technology options. The development of flight management systems further stimulated the study of optimum trajectories[24]. Again interest was directed at near-optimum solutions in this study which used optimisation methods to describe the sensitivity of various parameters.

Interest in the optimum design of commuter aircraft was shown by NASA[25] in the design of a 30 seat twin turbo-prop design and by Chacksfield[26] in the study of a range of aircraft configurations. It was around this time (1984) that Loughborough developed the original RAE-MVO method for the prediction of optimum flight profile for turbo-prop. commuter aircraft. Simos[27] and Jenkinson[28] developed two separate programs (GATEP for the preliminary design, and SCOPE for the flight profile optimisation) for this class of aircraft. The results of the work on flight profile optimisation was reported in 1985[29]. An extension of the work led to the two programs being joined together to allow, for the first time, a full configurational/operational optimisation[30] for commuter aircraft.

Many of the early studies on optimisation had indicated how such programs could provide a better understanding of the full aircraft model and the design process. To this end computer methods have been used in the teaching of aircraft design at Loughborough[31][32], Delft[33][34] and Berlin[35].

Continued interest in optimisational methods in aircraft design is shown by the papers to be presented at the next ICAS conference[36].

References concerned with the detailed aspects raised in subsequent chapters are listed at the end of the appropriate chapter.

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Chapter 3

COMMUTER OPERATIONS AND AIRCRAFT CONFIGURATIONS

3.1 Short-haul Transport

To understand the fundamental nature of the short-haul transport market it is worth reviewing the theory outlined in 1967 by Professor Bouladon[1] of the Battelle Institute. In his analysis of journey time against stage length for various modes of transport, he identified three "gaps" in the provision of transport. These are shown in figure 3.1 together with the characteristics for various types of transport. It is interesting to note that apart from minor innovations (e.g. horizontal escalators) there have not been any developments in the ensuing twenty years which have significantly altered this situation.

Smelt[2] in his paper on the air/ground transport split observed that all the curves on the Bouladon graph had the same characteristic shape. This results from the intrinsic delays in the journey block speed for various forms of transport. The curves can be repositioned horizontally by a change in journey speed, or vertically (more precisely moved along the 'walking' direction) by changes in delay time.

The gaps indicate a potential for dissatisfaction with the transport systems because they offer regions of worse service than the best trade-offs between time and distance. The problem areas are seen to include:-

(i) the pedestrian transport gap (1-2 miles) arising because travellers seem to object to the waste of time associated with walking more than about a kilometer.

(ii) the short-haul gap (around 200 miles) discussed below.

(iii) the long-haul gap (about 5000 miles) due to the boredom of travel lasting more than about 10 hours.

As travellers, it is easy to recognise these gaps but we may have personal preferences which adjust the distances quoted above.

The short-haul gap is particularly interesting because it embraces all four competing modes of transport (air, automobile, bus, rail). All modes are seen as unsatisfactory in meeting the demands even with recent improvements to each system. For the automobile, the introduction of fast motorway links has increased cruise speed but urban congestion has, at the same time, increased time delays at the start and end of the journey. Bus/Coach travel has been similarly affected. On rail, speeds have increased over recent years but frequency of service has reduced, again increasing the potential for delay. The net effect of these changes has been to only slightly narrow the original gap at the shorter distances and to make ground transport more competitive with air in the mid-range. There still remains a transport requirement at about 100 to 1000 miles which is not satisfactorily met by current ground or air systems. To some extent the slow speed propeller commuter aircraft operating at reasonable frequency, and specially commissioned charter and business flights, have developed over the past 20 years to fill the gap but these do not satisfy the total need.

For commuter aircraft design, this analysis points the way for future developments. Frequency and speed are the key elements to new operations. Both should be increased. For the short-haul airline this represents a dilemma since it implies smaller size and more expensive aircraft to meet a given market. This will lead to less favourable operating economics and more air traffic congestion.

The greatest influence on closing the gap would result from reducing delay time. This raises several aspects which are not directly related to aircraft design features:-

(i) reducing booking and pre-flight reporting time
(ii) reducing taxiing distances and/or increasing taxiing speeds
(iii) reducing in-flight ATC delays
(iv) reducing ground transport time from home destination to local airports.

Several attempts have been made to tackle these aspects (e.g. Shuttle service, STOL) but no significant improvement has yet arisen.

The need for short-haul travel remains strong and all the competing modes of transport provide different advantages. The automobile offers good flexibility in travel arrangements but is uncomfortable and time consuming over long distances. Rail and Bus operations are relatively cheap but suffer schedule and geographic limitations. Over the longer distances, restrictions in maximum speed of the rail and road systems adds time penalties and associated travel discomforts. Air travel avoids some of the penalties at the longer distances but suffers even more severely from the schedule and geographic penalties. As travellers become more familiar with the type of aircraft and operations for medium and long-haul flights, they become more critical of the older types of commuter service. They demand equivalent passenger cabin comfort (space and quietness) and will not tolerate the turbo-propeller noise intrusion into the interior of the aircraft. They object to the (relatively) more turbulent flights of unpressurised aircraft with lower wing loading flying at low altitudes.

3.2 Short-haul aircraft

To identify the significant factors affecting short-haul air transport operations, NASA commissioned a detailed study of commuter-airline operations (Small Transport Aircraft Technology, STAT)[3] [4]. The important technology dependent factors that were identified (essentially for aircraft) can be related to all modes of transport. The list for passenger and community acceptance includes:-

1. Convenience
2. Dependability
3. Speed
4. Ride Quality
5. Noise & Emissions
6. Safety
7. Fare

These factors must be carefully considered against those associated with operational economics:-

1. Productivity:-
   - 1.1 Short-field capability
   - 1.2 ATC interface
   - 1.3 Block time
   - 1.4 Payload fraction
2. Fuel economy
3. Maintenance
4. Aircraft price

Many of the factors in the two lists are contradictory. At the time of the study (late seventies) the price of fuel had suddenly risen and was shown to dominate the aircraft operating cost breakdown (representing about 36% of DOC). In the subsequent decade fuel cost dropped to about one third of the maximum price achieved and, although still significant, is no longer dominant. Nowadays, aircraft standing charge is the most significant component of cost. Design effort is again directed at the traditional aircraft manufacturing aspects (increased reliability, extended life, low first costs, aircraft productivity etc).

Apart from the technological factors, the STAT study identified several other operational aspects that raised concern with providers and users of the system. These included:-

- i Financing costs
- ii Government subsidy
- iii Regulatory uncertainty
- iv Market uncertainty
- v Terminal facilities
- vi Security

Many of these problems are not unique to short-haul air transport operations. The list highlights the non-aircraft design factors that influence the development of the business.

It is worth considering in the next section the development of the commuter airline business to more clearly understand these aspects.

3.3 Development of Commuter Airtransport Operations

Air transport is expected to grow strongly in the next decade[5]. Annual growth rates in excess of 5% have been projected by ICAO up to the turn of the century. Much of this growth results from the increasing affluence in the developed and developing worlds but new political opportunities will even further stimulate the airline business.

Like many other industrial and commercial activities, commercial air transport has its origins in the United States and this market still dominates the business. New relationships between governments in Europe and in the countries around the Pacific basin will have increasing influence in future expansion. It is worth studying the development of the US market, not only because this still represents 80% of the total business but also to draw conclusions for analysis of other markets (particularly Europe).

Regulation of the airline business in USA has roots in the formation of CAA (later CAB) prior to WW2. This body provided 'Certificates of Public Convenience and Necessity' to airlines and thereby initiated the Major Trunk Carriers. As the air-travel business grew these airlines became bigger and they tended to concentrate their operations on the larger connubations to the detriment of service to the small communities. After WW2 the US government instituted a new type of 'Local Service' airline with less legislative regulation than that imposed on the trunk carriers. These regional airlines also grew and like their predecessors neglected the less popular (less profitable) services. The Deregulation Act in 1978 was intended to make entry into the airline business easier in a direct attempt to stimulate the provision of services in the less developed parts of the country (third-level airlines). These were designated Commuter Airlines and more recently have become known as Regional Airlines. The legislation was successful as the number of independent airlines increased in the early 80's. A number of these became so proficient at generating regional networks that the major carriers recognised the commercial advantages of forming business associations with them. Using the airports of the major airlines as the hub and the regional network as the spokes, the majors could automatically feed passengers into their services (now known as 'interlineing'). Initially the majors linked their commercial interests with the regionals by operating code-sharing arrangements. Many of theses arrangements are still in operation.

Subsequently the majors have taken-over, bought-out or amalgamated the most successful regional carriers and this has reduced the total number of independent regional airlines operating. Some commentators[6] project that most of the independent airlines will find the competition from the 'owned-regionals' too fierce and will be forced into the less profitable non-hub sector. This will be accelerated as computerised booking systems are exploited by the major airlines. According to FAA statistics[7] the current 'top 50' regional airlines already account for 94% of the US regional traffic. The advantage of this business to the majors, can be judged by the fact that 75% of regional passengers transfer to major airlines at one or both ends of their journeys.

These links between the regional and major airlines will have considerable influence on the provision of new aircraft for the commuter market. The stronger purchasing power of the bigger airlines will make aircraft sales competition even stiffer. On the other hand, the regional passenger will expect improved comfort and service standards (commensurate with the major flight sectors), a good frequency and a reliable service. The increased business that is predicted will cause air traffic congestion at the hub airports which may dictate larger aircraft. Unless block times can be shortened this may cause reduced frequency for the same volume of traffic. The increased number of flights at the hub airports will further sensitise the environmental aspects (particularly aircraft noise). This may also influence aircraft equipment choice and restrict older/larger jets in the regional network. These aspects were raised by Boeing in their promotion of the Dash 8 derivitives[8]. They identified a gap in the market at 60-100 seats with high block speed over a 500nm stage. (Only partly met by their aircraft!).

In Europe and elsewhere the development of the short-haul air transport market has been hindered by national boundaries (sovereignty). International law insists that scheduled air services between the two countries can only take place through bi-lateral agreement. These often carry non-competitive clauses to protect the weaker airline and this makes many routes less profitable (even with much higher fares than would be charged in US) due to reduced demand.

In the mid-'80s the EEC passed a Directive[9] to stimulate the growth of regional air services in the community. After a long and difficult four year period of discussion between member states the EEC adapted the directive in June 1983 and it came into force in October 1984. Sovereignty of the airspace over a country and the restriction of passage of non-national transport has long been held as a symbol of independence by all countries. The delegation of these rights to the Commission was not proposed but an agreed code of practice affecting the use of community airspace was agreed. European rules, as laid down in the directive, safeguarded national rights within an operational framework. In effect the coexistance between the sovereignty of airspace of an EEC state and the regulatory body of the commission is assured. Within these safeguards a member state must now justify the refusal to develop air services. To protect the established scheduled services operated under traditional bi-lateral agreement and other special cases new inter-regional services cannot be automatically granted if:-

(a) the aircraft to be used are larger than 70 seats

(b) the stage distance is less than 400 km

(c) they operate from airports within a 50 km radius of an equivalent scheduled service.

New services must operate from regional (category 2/3 ECAS) airports and foreign competition must accept reciprocal arrangements from the national flag carrier. Much of the legislation is concerned with state subsidy and anti-dumping.

Due to the sensitive nature of the sovereignty issue the directive is considered as moderate and commercially cautious but may present a foundation for innovative inter-regional services in the future if further harmonisation can be agreed. This should include the development of Eurocontrol (ATC), joint airworthiness standards (JAR), joint operational standards and improved airport standards.. The development of the single market in 1992 and the recent political changes in the rest of Europe provides optimism that in the near future short-haul air travel will increase even more quickly than forecast.

The relative failure of the EEC Directive to stimulate regional air services since 1984 is proof that regulatory conditions alone are not sufficient incentive. For such policies to be successful, technical, economic, financial and legal aspects must be centrally controlled. This would imply further loss of sovereignty (not only for airspace but also concerning exchequer aspects) and most states are not yet ready to delegate these matters to the European authority (particularly UK!).

Several other factors may also apply when comparing the European and American commuter operations. Not least of these is the strong competition in Europe from surface modes. These are not only more developed than in U.S. but also enjoy a higher customer acceptability and considerable state subsidy. European travellers seem to be less'air-minded' than their American counterparts but this may be due to fare price sensitivity since in the charter sector no such characteristic is seen. The tradition of good and reliable road and rail services in Europe will always present a serious challenge to air travel.

In summary, the market for short-haul travel remains strong and is seen to have potential for improvement. Such improvement may arise from technological advances in vehicle design (and operation). The STAT study shows the factors which dominate the situation, some of the most influential of which lie outside the area of aircraft design. Despite urban congestion, competition from ground transport will remain strong and it will be necessary for the industry to be innovative in the production of new aircraft types. These will include the development of new technologies in faster and larger commuter aircraft.

3.4 Development of Commuter Aircraft

Although it is convenient to categorise aircraft in terms of their passenger capacity, the influence of range on the overall design should not be minimised. Available published data on aircraft range capability is unreliable because the corresponding payload condition is not often quoted. Fortunately, particular series of aircraft have similar range specification so may be compared. Figure 3.2 has been compiled to show the development of aircraft in the size typical of commuter operations.

The design of commuter aircraft stretches back to the very first commercial transport aircraft but it is the period after WW2 that provides the most direct links with modern designs. In the immediate post-war period converted military transports, of which the ubiquitous DC3 is the most notable, with nearly 11000 produced, provided a pool of aircraft to prime the re-emerging civil aviation business. These were challenged in the early 50's by the introduction of several new aircraft designs, particularly from the newly emerging European industry (Britain, France, Holland). In the 40-60 seat size the early success of the Viscount was not significantly exploited and the Convair 340/440 and other models offered strong competition. Toward the end of the decade a trio of twin-engined turbo-propeller aircraft were introduced (Handley-Page Herald, Fokker Friendship F27 and Avro 748) all powered by the new Rolls Royce Dart engine. These were later joined by the slightly larger Japanese designed YS-11. This provided a product base which was not to be seriously challenged for over twenty years.

The success of early turbo-jet aircraft and the development of more efficient engines led to the design of the BAC One-Eleven, Boeing B737 and Douglas DC9. The subsequent introduction of the more efficient turbo-fan engine has prolonged the life of the latter two designs which are still available (albeit in larger versions than considered in this review). The 60's and 70's heralded the design of a new set of utilitarian designs aimed at the "less than 19 seat" aircraft classification, the Shorts Skyvan, Beech 99, Czechoslovakian Let 410 and finally, but most significantly, the Brazilian Embraer Bandierante. These designs also formed a product base which dominated the market until the early 80's when modern versions of these types and some entirely new designs entered the scene.

The only competition to the established designs in the medium size (40-60 seats) came from innovative layouts. This period (mid 60-70) saw the introduction of the first turbo-jet designs F28 and VFW 614 in this size. The 40 seat VFW design was particularly innovative with over-wing engine position. It was regarded by some to be ahead of its time. Increased costs including the sudden rise in fuel price in the late 70's made the small-size turbo-jet aircraft only competitive in those markets in which time saving was at a premium (e.g.business/executive travel). The second innovation in this period was concerned with short take-off and landing (STOL) in the form of the DHC Dash 7 aircraft. This also was a design ahead of a strong market for this type of technological advance. Apart from operation in some specialised locations, the inherent penalties of increased weight and complexity arising from the high-lift system were not seen to be necessary. As airport congestion problems increase, the demand for this type of technology may be resurrected.

The introduction of several new designs at the start of the 80's was largely in anticipation of the expected expansion in the market following deregulation in USA. In the 30-40 seat size, Shorts redesigned their SD330 aircraft to carry 36 passengers and CASA, Embraer, Saab and DHC came into the market. In the medium size (40-70 seats), a French/Italian consortium developed the ATR42 , Fokker developed the F50 and British Aerospace redesigned their aging HS748 aircraft to produce the advanced turboprop (ATP).

The expected expansion of the market in the 40+ seat sector has continued to stimulate many manufacturers to further develop their models into faster and larger aircraft. Saab have announced their fast-turboprop (2000), DH Canada (now Boeing) have announced plans to expand their Dash 8 aircraft to 50 and then to 65 seats. The ATR consortium have already stretched their design to 70 seats (ATR 72) and are now considering the 82 seat version. LET have expanded their 19 place aircraft to 40 seats. All these aircraft are turboprop powered yet it is known that customers prefer the advantages of jet aircraft speed and comfort. To offer this option several manufacturers (Canadair, Embraer and Shorts [later withdrawn]) projected new turbo-fan designs (approximately twenty years after the premature introduction of the VFW aircraft!). All these aircraft use two engines. The four-engine variant already exists in the form of the British Aerospace 146. This design started as an 80 seat aircraft, seemed destined only to grow to larger sizes, but recently has been projected in a reduced capacity model to compete with the new fan-jets as they are stretched.
One of the interesting features shown in figure 3.2 is the predominance of European compared to American manufacturers; especially as 80% of the market for such aircraft rests in the USA.This point was raised in the STAT studies(3) (10) which tried (in vain) to stimulate US manufacturers into the market.

It is always difficult to identify trends from a survey of this nature as unpromising aircraft sometimes blossom into success. The Jetstream, when first introduced, was poorly regarded but the developed version (-31) became the US market leader and the new design (-41) looks very competitive. The DHC Dash 8 which was originally a struggling design must now be a very strong competitor in the market, especially when fully stretched and coupled with the Boeing marketing experience.

Figure 3.2 also shows the potential for expansion of the market. The solid (fan) lines represent +5% per annum growth, as predicted by British Aerospace[11] in 1979 and still confidently expected. By the 90's, the original Viscount market is seen to have stretched to the BAe 146/F100 size. The DC3 size has expanded to the current 50 seat market and the 15/19 seat band is seen to grow to 30 seats.

In order to assess the technical factors influencing this group of aircraft (15 - 115 seats), a number of different aircraft characteristics have been analysed using data from various issues of Janes[12] and some recent journal reviews[13][14][15]. The aircraft have been grouped into the four classifications listed in figure 3.3. This list is my personal selection of aircraft types which have made significant contributions to the development of commuter aircraft since the war. Technical data for all but the Historical group is listed in figure Appendix B (B1 (old types), B2 (current aircraft) and B3 (new and projected designs)). For the current aircraft list only, several derived parameters have been evaluated and are also listed in Appendix B (figure B4). In each of these figures sheet 1 provides the data in SI units and sheet 2 in Imperial units.

With such a disparate set of aircraft types it is not surprising that no obvious technical conclusions can be drawn from the data. The most consistent relationships obtained from the data are shown in plots of number of seats versus maximum take-off mass (figure 3.4), aircraft operational empty weight (figure 3.5) and aircraft price (figure 3.6). The ±10% sensitivity about the best-fit line indicates the lack of accuracy that is associated with such crude parameterisation. At the smallest size of aircraft (15-21 seats) the mass data is seen to spread locally about a ±35% region! Plotting cruise speed against seats (figure 3.7) shows the trend of new designs towards faster cruise and hence reduced block time.

Relying on the published data provided by the manufacturers may account for some of the variability seen in the data list. As mentioned earlier this inconsistency becomes particularly apparent when considering the performance parameters which depend upon specific definitions. Field and range are examples of this phenomema since in both cases the aircraft weight, payload, fuel load, air temperature and altitude have considerable influence on the quoted values. Figures 3.8 (Field) and 3.9 (Range) show the scatter of the data. The only conclusion that could be drawn is that the larger size aircraft in general, fly longer ranges and have longer field lengths.It is unnecessary to perform such a detailed analysis to be aware of this relationship.

In an attempt to draw some rational conclusion from the data a series of derived values was compiled (appendix B, figure B4) for current aircraft.
The following parametes were determined:-

Weight per passenger (MTO and OEW)
Empty weight fraction
Wing aspect ratio
Wing loading
Span loading
Productivity (Passenger x Speed/Aircraft Weight)
Cost parameters (Weight/$, Passenger/$)

The weight per passenger parameters are plotted in figure 3.10 (OEW/PAX) and 3.11 (MTOW/PAX). The empty weight ratio shows more consistency than MTO but no direct relationship can be established. The weight fraction (OEW/MTOW) shows more consistency than the per-passenger graphs. The high average value of 61% coupled with approximately 25% allowance for the passenger weight ratio, gives a high zero-fuel weight fraction. This is of concern to designers and signals a high degree of sensitivity to weight change for such aircraft. The wing aspect ratio values show the tendency for higher values on turbo-prop designs and lower for turbo-fan aircraft. This may be partly accounted for by the higher speeds of the latter type. Ignoring the values of the larger turbo-fan aircraft, the wing loading averages 276 (Kg/m) and span loading averages 576 (kg/m). As may have been anticipated, wing loading shows more consistency due to less dependence on installed power effects. In an attempt to define productivity for these aircraft, the classical productivity parameter of [seats x cruise speed/aircraft weight]. Aircraft MTO has been used in the equation because the available data did not give fuel weight. Again, inconsistency in the definition of some of the cruise speeds and the lack of an accurate value of fuel weight makes the parameter values highly variable. Finally the data was analysed to determine cost parameters. Weight per $ averages 1368 (Kg/$M) which translates to 731 $/Kg. This is slightly higher than the value used in the synthesis module which was based on earlier data and reduced slightly to reflect Shorts experience in the manufacture of such aircraft. The number of passengers per $ evaluation varied from above 8 to about 5 (PAX/$M).
No firm conclusions could be drawn from the results.

All of the parameters listed above were considered in the analysis of the market for 40 to 70 seat commuter aircraft conducted by Legg[16]. Where appropriate, the relationships determined by Legg have been cross-plotted on figures 3.4 to 3.11. As shown, these values fall within the representative data range of the published data but again no firm conclusions could be drawn.

In summary, the analysis of the aircraft data did not provide any acceptable technical relationship that could be used for the design of commuter aircraft. There may be several reasons for this including the variability of the aircraft types that were considered, the inconsistency in the published data, the inherent differences in the basic specifications and the intrinsic technical competence of the different design teams.

The data does show that groups of aircraft designed by different manufacturers in the past, to meet a particular market sector, have been of similar layout. For example the Herald, F27 and HS 748 were each powered by twin-turbo props which were conventionally mounted on the wing whereas, the BAC111, DC9 and B727 were all rear fuselage engined turbojet designs. It would be too simplistic to assume that such consistency arose from detailed technical optimisation since many other factors intrude into the selection of the aircraft configuration of which current trends (fashion) may play a larger part than the technologist would confess.

The new set of communter aircraft designs (FJX, RJ, Emb.123) all have different configurations. The RJ aircraft has rear fuselage mounted engines and the other two although both wing mounted have under-wing and over-wing layouts. Since the RJ and Emb123 aircraft are developments from existing types their configuration may have been dictated by the earlier design. Maybe the next generation of commuter aircraft will provide a coherent choice of layout which is obviously denied to these initial designs.

These considerations point again to the difficulty of using existing aircraft technical data in the projection of new aircraft types and confirm the conclusions from the analysis of data above.

Before concluding this section, there is a common fallacy which must be corrected, regarding the types of aircraft used by regional airlines. These are no longer old and second-hand aircraft, 'handed down' from the majors. In data presented by Mike Ambrose(17) (Director General, European Regional Airlines Association) the average age of aircraft used by his members is 7.7 years and more than 50% of the total fleet is less than 5 years old. This represents further evidence that the market is expanding rapidly and creating a strong demand for new aircraft that are specifically designed to meet the special conditions that apply to commuter operations.

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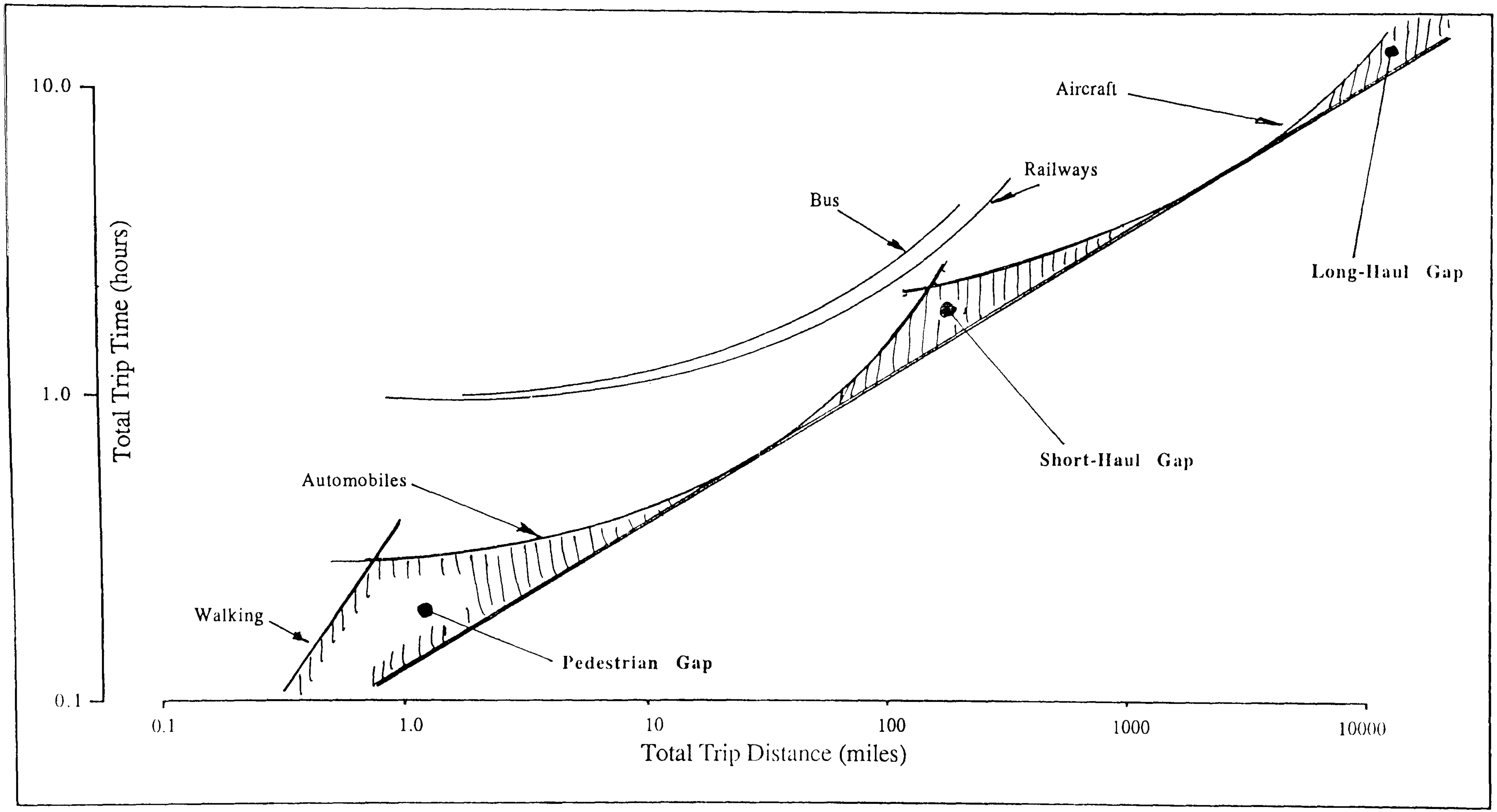

Figure 3.1 Transportation Gaps (ref.1 Bouladon)

Figure 3.2 Historical Review of Aircraft (with lines of +5% growth from 1950 shown)

Historical	Old	Current	New & Projected
Douglas DC3	1. Shorts Skyvan -SD7	21. B.Ae. Jetstream -31	41. Embraer/FAMA -CBA - 123
Vickers Viscount -700	2. DHC Twin Otter -DHC6-300	22. Dornier 228-202	42. B.Ae. Jetstream - 41
Vickers Viscount - 800	3. Beech 99	23. Beech -1900	43. (Shorts - FJX)
Convair 240	4. Let 410	24. CASA - CN212	44. Canadair - RJ
Convair 330 & 340	5. Embraer Bandeirante -EMB110	25. Shorts -5D360	45. Saab - 2000
Convair 440	6. Shorts -5D330	26. Embraer Brazilia - EMB120	46. DHC Dash - 400
D.H. Comet 3	7. VFW 614	27. DHC Dash 8 -100	47. Dornier - 328
Sud-Av. Caravelle	8. Fokker - F28	28. DHC Dash 8 - 300	48. Embraer - 145
Lockhead Electra	9. DHC - Dash 7	29. Saab - 340	49. MBB/MPC - 75
Handley-Page Herald	10. Beoing B737-100	30. ATR 42	50. Fairchild (Metro V)
Fokker -F27	11. Douglas DC9 - 30	31. ATR 72	
Avro 748	12. BAC One-Eleven - 500	32. BAe - ATP	
YS11		33. BAe - 146/200	
		34. Let 610	
		35. Fokker - F50	
		36. Fokker - F100	
		37. CASA - CN235	

Figure 3.3 Aircraft Categorisation

Figure 3.4 Survey of Aircraft Data [MTO/PAX]

Figure 3.5 Survey of Aircraft Data [OEW/PAX]

Figure 3.6 Survey of Aircraft Data [Selling Price]

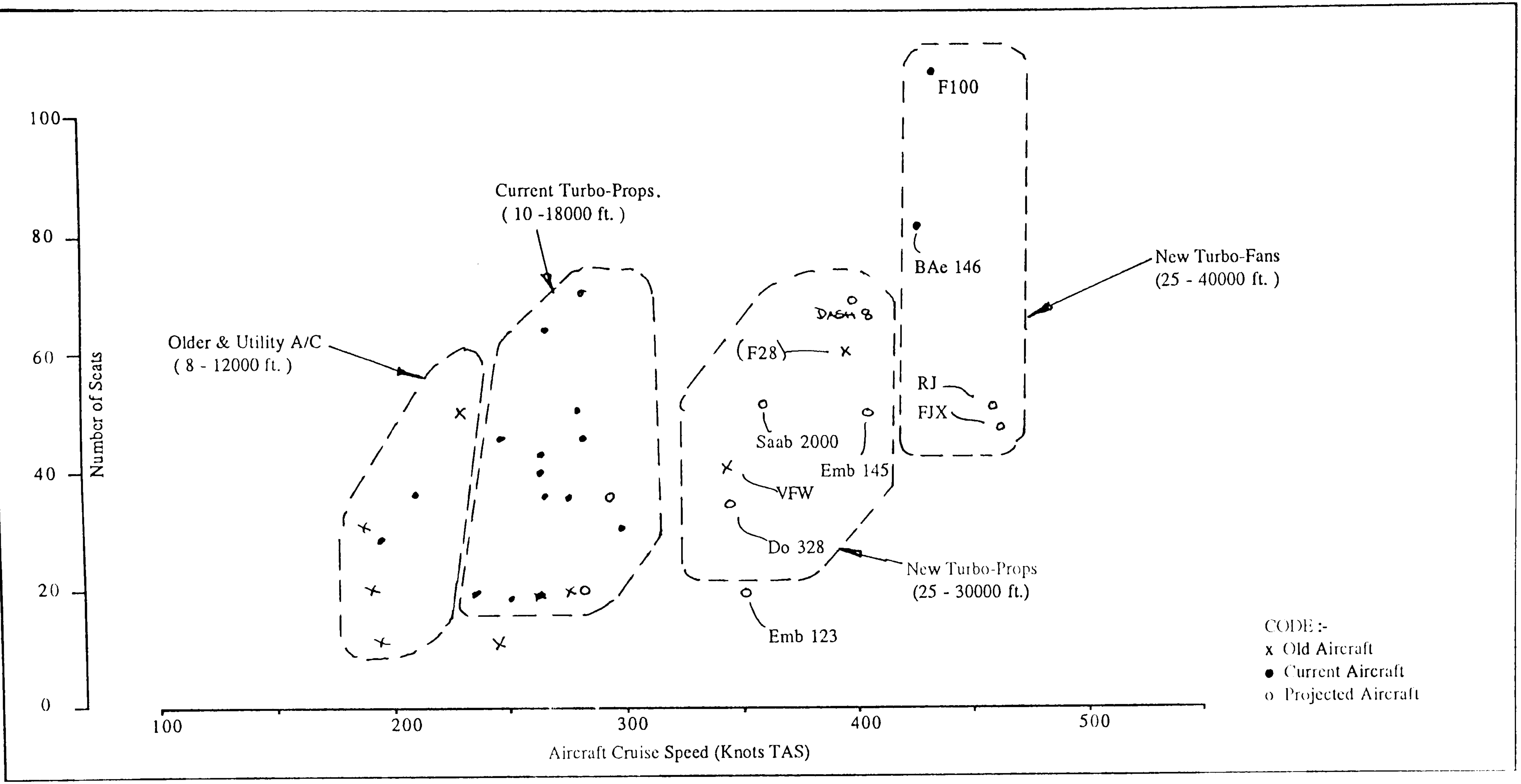

Figure 3.7 Survey of Aircraft Data [Cruise Speed]

Figure 3.8 Survey of Aircraft Data [Field/PAX]

Figure 3.9 Survey of Aircraft Data [Range/PAX]

Figure 3.10 Survey of Aircraft Data [OEW/PAX Ratio]

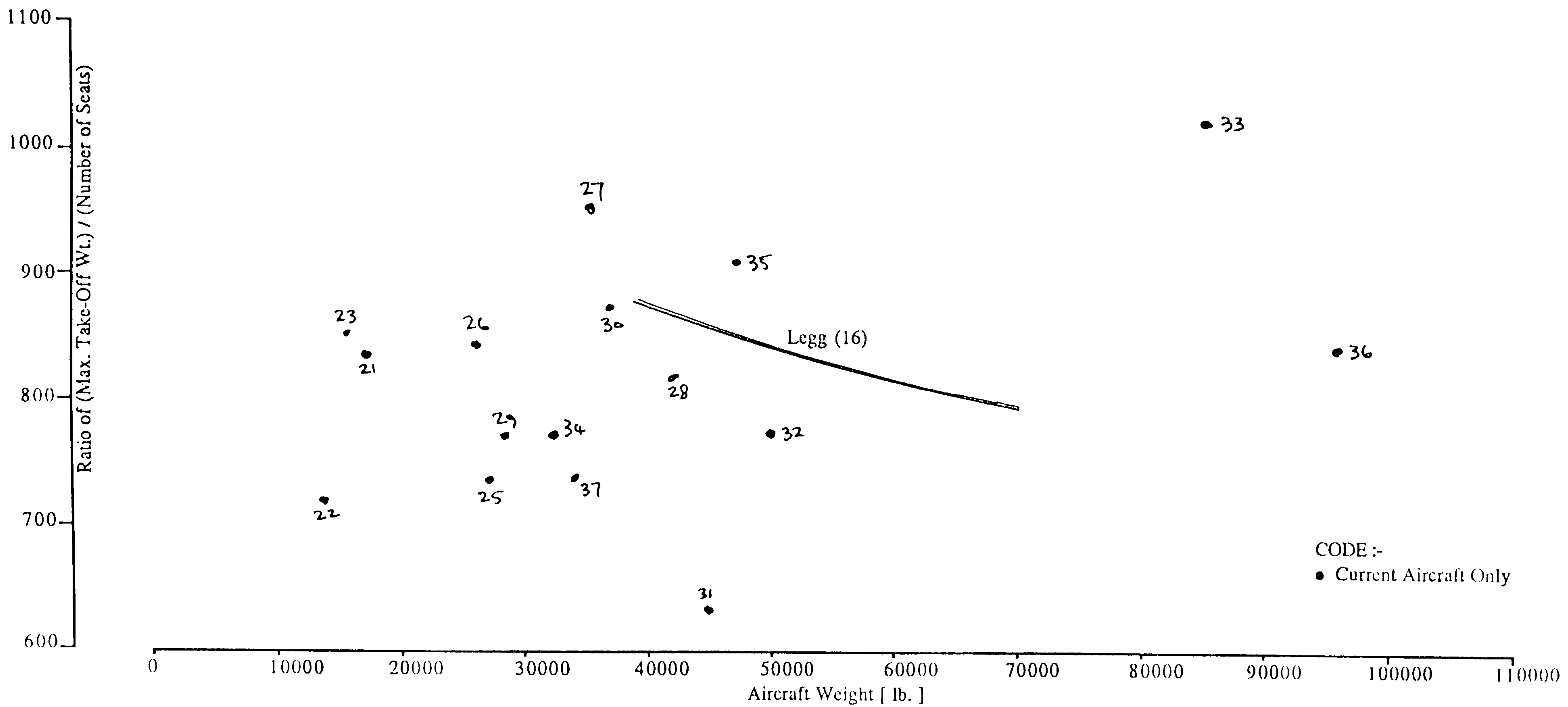

Figure 3.11 Survey of Aircraft Data [MTO/PAX Ratio]

Chaper 4:

OPTIMISATION METHODS

Modern commercial aircraft manufacture and operation is performed in a highly competitive environment and is subject to many constraints. It is essential to use methods of analysis that establish efficient performance for the total aircraft system. For civil transport aircraft, this need translates into the maximisation of return on investment. From an engineering standpoint this means increasing revenue potential at the same time as reducing operating costs within a set global financial framework.

For aircraft, the traditional methods of optimisation have concentrated separately on either the aircraft configurational specification *(Design Optimisation)* or the determination of aircraft operating procedures *(Flight Path Optimisation)*. For design optimisation, the flight path and mission characteristics are prescribed and treated as part of the input specification. The optimisation methods involve a systematic search of the values for the design variables, to identify the best value of the overall design criterion. Flight path optimisation is concerned with the identification of the most efficient method of operating the particular aircraft system. Methods of analysis are relatively straightforward and are concerned with the evaluation of the flight path dynamics of the aircraft. The aerodynamic and propulsive characteristics are assumed to be prescribed by the aircraft configuration. From the infinite number of combinations of speeds, heights, power settings, flap deflection angles etc, the optimisation method must select the one which gives the best prediction for the overall criterion. Both types of optimisation will be constrained by airworthiness, air traffic control and business regulations which must be reflected in the analytical model employed.

The analytical methods used for design and operational estimations are similar. Only subtle changes in emphasis are necessary between the two types of analysis. It is therefore possible to link them together to conduct a single optimisation that considers all variables and constraints simultaneously. This is the procedure adopted in this thesis. Multivariate optimisation techniques are employed to predict the most efficient choice of aircraft parameters (e.g. wing area, engine size, climb and cruise speeds etc.) for a chosen criterion (e.g. minimum direct operating cost per flight, minimum fuel useage etc).

4.1 Selection of analytical methods

It is essential to select methods of analysis that are matched to the requirements of the optimisation task. The procedures must be capable of evaluating the various parameters to a significant level of accuracy. If the method is too crude, the optimiser will have difficulty in making sensible progress over the design surface. On the other hand, if the method is too complicated the computational time will extend and fewer design points will be determined in the time available. The assembly of methods of analysis which together provide acceptable estimations (in terms of accuracy and sensitivity) is a crucial stage in the development of optimisation techniques.

Of all the analytical areas that are considered in the full optimisation method (including mass estimation, cost prediction, aerodynamic analysis, propulsion evaluation) that of aircraft performance shows the above compromise best. Thelander(1), in his description of performance analysis methods, identified four classes of operational problems:

(a) *Generally dynamic* - in which the flight conditions are non-steady throughout the entire mission. Non-spherical earth effects and anomalies of the gravitational field may be considered. Performance estimation is precise but complex. These methods are only used when the required vehicle performance is critically dependent on the flight path. Specialised high performance and highly manoeuvreable vehicles are the main interest of this class (e.g. spacecraft boost and re-entry, hypersonic aircraft and some missile systems).

(b) *Predominantly dynamic* - involves the operation of high performance aircraft with many mission segments and frequent manoeuvres. These manoeuvres may be non-steady and have a significant influence on the aircraft flight path and performance. Climb-zoom flight profiles and energy management methods for transonic and supersonic aircraft would be considered in this class. It is important to identify the main dynamic segments and to apply appropriate analytical methods. These methods are used for military aircraft and missile performance analysis.

(c) *Predominantly procedural* - include the conventional performance analysis and operating procedures for subsonic aircraft. The flight paths of these aircraft are considered as several separate segments of steady, relatively unaccelerated, phases joined by modest transitional manoeuvres. Although performance gains per flight are regarded as potentially small, when summed over the total aircraft life the total gain is significant. Inaccuracy in accelerated climbs and decelerated descents when considered as quasi-steady segments may be reduced by considering multi-segmenting of these phases. This is necessary for aircraft in which climb and descent represent significant features of the total flight profile (e.g. short-haul transport aircraft).

(d) *Special situations* - include all performance estimations not forming part of the normal flight profile analysis (e.g. procedural demonstration flights, emergency and safety checks). This class does not usually warrant optimised performance analysis.

Clearly, commuter aircraft flight profile analysis may be considered in the *procedural* class. Each of the flight stages (take-off, climb, cruise, descent and landing) may be considered as separate segments with the acceleration and deceleration approximated by multiplexing the climb and descent stages. The effects of manoeuvres between the stages is allowed for by the addition of time and fuel penalties in the take-off and landing segments.

This description of the flight profile and operating procedures may be regarded as the ideal profile. In practice the ideal would be compromised by physical and control system constraints (e.g. air traffic regulations). Further modifications to the flight operations procedures would also follow from specific flight planning considerations (meteorological, aircraft loading etc). Since all these departures from the ideal are related to particular flight conditions it is unacceptable to incorporate them in the general optimisation program. Once the optimum procedure has been established it is possible to introduce constraints equivalent to real restrictions and thereby evaluate the penalty incurred by these effects. For example, penalties due to a restriction on cruise height imposed by air traffic control, or the changes imposed in the climb segment to comply with noise abatement procedures, can be assessed. The ideal profile will show the aircraft speeds, rate of ascent (and descent) and engine setting variation with height for the climb and descent phases. It will also show the speed and height conditions for cruise.

4.2 Problem Formulation

The types of optimisation method used for the design and trajectory problem has traditionally been different. For the **aircraft design** case the overall criterion *(objective function, OF)* is expressed as a function of a number of *aircraft parameters* (x):-

$$OF = f(x_i), \qquad \text{(where, } i = 1 \ldots\ldots\ldots n\text{)}$$

The objective function can be considered to be evaluated in *n* - dimensional Euclidean space and the parameters can be interpreted as a vector *x* (sometimes referred to as the *control vector)*. As the aircraft parameters assume different values, *x* will vary as the objective function varies. The values of the objective function can be regarded as defining a surface in the *n* - dimensional space. This surface is referred to as the *design surface.*.

In all cases some boundaries will exist in this space due to limitations (*or constraints)* on individual parameters, or sets of parameters in combination.

The problem is therefore exactly defined as the selection of the vector x which extremises the objective function (i.e. maximises or minimises depending on the nature of the objective function) within the feasible region of the design surface. The individual values of the design parameters together with any constraints define the optimum aircraft design.

The traditional method of optimising the **aircraft trajectory** is associated with an array of ordinary differential equations:-

$$\frac{dx_i}{dt} = f \quad (x_i \, , \; u_i)$$

- in which x_i represents the aircraft state variables and u_i the control variables.

The optimisation task is concerned with finding the control variation with time that extremises a selected objective function in a given time interval:-

$$OF = f \left[\int_{t_1}^{t_2} f \quad (x_i, \; u_i) \; dt \right]_{optimum}$$

Fortunately, for commuter aircraft the trajectory problem can be solved using kinematic, in place of dynamic, aspects and hence the optimum flight path can be evaluated using the same optimisation method as used for the design problem. In this way, the flight and control variables are treated as straightforward variables and constraints in the design space and solved in combination with the design variables.

Stepniewski [(2)] describes the multivariable search techniques that were available in the early seventies. It was customary at this time to select a particular type of search appropriate to the anticipated nature of the design surface. Boeing, in their AESOP program, constructed an automatic selection procedure which optimised the search efficiency. In the mid-seventies Purcell [(3)] with others at RAE developed new optimisation procedures mainly aimed at the aircraft project design area. Their SUMT (sequencial unconstrained minimisation technique) program was further developed in the mid-eighties to enlarge the problem areas (handle more variables and constraints) and increase the search speeds. Strobanski [(4)] (et al) improved the original RAE-MVO program and produced the RQPMIN (recursive quadratic programming) method. This is the optimising routine used in this thesis. This method was chosen because several years experience had been gained on the earlier RAE method. The method was available, well documented and used by other researchers in the aircraft design field. The program was found to be easily transportable to various computer systems. In reviewing the original choice it was concluded that the RQPMIN program would still be the first choice if this type of work was to be started now.

4.3 Executive program description

A full description of the RQPMIN program is available in the RAE user manual[4]. A brief summary is given below:-

The method is essentially a gradient-search procedure which progressively matches the step size to the progress along the design surface. An unconstrained design surface is assumed. All constraints are accounted for by the introduction of a penalty function added to the objective function (figure 4.1). At subsequent stages of the search this penalty function is 'tightened' to allow the search to move closer to the constraint boundary. The combined objective function can be defined as:-

$$OF^1 = OF + \sum_{j=1}^{n} \chi_j^r$$

where:- χ_j is the array of constraints
r is a power term which is conditioned by the search path.

The constraints may be of the equality and inequality type.
All design variables are limited between lower and upper values:-

$$x_{i_l} < x_i < x_{i_u}$$

To avoid the absolute values of variables, constraints and objective function interfering with the sensitivity of the search, they are all normalised to near unity by the introduction of scale multipliers. In this way all variables have intrinsically equal influence on the design surface search.

It is unusual for this type of optimisation to find the absolute optimum point. The search strategy utilises a tolerance on the repeated evaluation of the objective function. The search is continued until either the design slope is equal to or less than the tolerance (figure 4.2) or there is no further progress possible (figure 4.3). The assignment of the tolerance value is a critical aspect of the problem definition. If the tolerance is too fine the search will not be completed in the allowable number of steps. If it is too crude, the accuracy of the optimum design will be suspect.

Since the constraints are treated as continuous functions it is unlikely that the evaluated design point will lie exactly on the theoretical constraint boundary. The optimiser requires a second tolerance be specified which dictates the acceptable displacement of the optimum point from the boundary. The same considerations apply to this tolerance value as described above for the objective function tolerance (figure 4.4). Edwards [5] described the effects of tolerance selection and the stability of the original SUMT optimiser and showed how these may lead to substantial variability in the selection of the optimum design point (as illustrated in figures 4.2, 4.4).

To commence the search an initial design point is required by the program (i.e. starting values for each design variable). It is conceivable that this chosen point resides in a position on the design surface which violates one or more constraints (an unfeasible region). The first procedure of the optimisation method is designed to check the feasibility of the starting point and to adjust the values of the variables if it is seen to be in the unfeasible region. The starting point is modified to progressively reduce the offset vector from the violated constraints (figure 4.5). When the point moves into the feasible region the optimisation method changes to the conventional gradient slope techniques and the search path is restricted to always stay within the feasible region. It should be noted that it is possible to arrange the problem definition in such a way that no feasible design surface is available.

Significant computer time may be involved in moving the initial point into the feasible region. For on-line studies it has been found useful to use the output values of the design variables from the previous study as the starting point for the next. Care must be taken to ensure that the tolerance effects described above do not mask the subtle changes investigated between individual close-study points. To guard against these effects extra searches are necessary starting the problem from a significantly different point.

The basic optimiser (RQPMIN) as developed by RAE will only output the optimum aircraft specification (i.e. the values of the design parameters at the point in the search when the design surface slope is at or below the tolerance value). In general, the designer would like to know more about the design than just the optimum point. For example he may wish to progressively relax one or more of the design parameters to assess the sensitivity of the design to these changes. Although the program outputs the values of the derivatives of the variables at the design point it is difficult to relate this information to the real design task. To allow the designer to perform a manual search around the optimum point the program was modified to permit single-passes to be made through the design model. Repeated application of the single-pass facility and storage of the output values in a database offers the possibility of investigating specific changes to the design.

A further alteration to the program was made to allow the design surface near the optimum design point to be displayed (see section 4.5). In this way the sensitivity of selected design variables to changes in constraints, and the sensitivity of the output parameters to the design variable values can be seen. This facility offers the designer knowledge on which to re-assess his selection of problem constraints and parameters and to investigate near-optimum *(PERI-OPTIMUM)* design points.

This removes one of the main criticisms of optimisation methods (i.e. information on non-optimum, but still acceptable, design choices is made available).

The architecture of the program is shown in figure 4.6. After calling various program administration modules (e.g. array normalisation, common block generation, block data input), the main aircraft synthesis module (USERF) is executed. For a single-pass study the resulting program output is printed and the program ends. For an optimisation study RQPMIN is called. This progressively adjusts the values of the variables and repeatedly calls the aircraft synthesis module. At the end of the optimisation routine, the final values of the program variables and output parameters are printed.

If a plot of the design surface around the optimum point is required, the program transfers to the PERI-OPT routine.

A detailed description of both the aircraft Synthesis Modules and the PERI-OPT program is contained in appendix C and sections 4.4 and 4.5.

4.4 Description of aircraft Synthesis Modules

The aircraft design equations are contained in the sub-routine USERF. The aircraft fixed data values are read into the problem common blocks, in subroutine SUB1. The engine fixed data values are read into the problem common blocks (thdata, ffdata) in subroutine DATAIN (BL1T02, BLCOST, BLSEG, EN, ENG). Several other subroutine and functions are called directly from the main USERF routine.

The aircraft design program can be considered as ten separate but inter-related modules:-

1. Input of aircraft data
2. Geometry calculations
3. Mass estimation
4. CG and balance calculations
5. Aerodynamic analysis
6. Stability analysis
7. Engine data interpretation
8. Performane estimation
9. Cost estimation
10. Output of all results

Each module is described in detail in appendix C, and a brief outline is presented below.

1. *Input*

This consists of five blocks of data

(i) a set of fixed data values for some of the aircraft geometry, mass, aerodynamic, mission and cost parameters,

(ii) a list of design variables with upper and lower limtis specified together with the starting value for the optimisation search,

(iii) a list of problem constraints with appropriate values,

(iv) specification of the choice of optimisation objective function,

(v) a set of values used to control the optimiser and the search tolerance.

2. *Geometry*

This section evaluates the fixed aircraft geometry from the input values. Each component (wing, flap, fuselage, empennage and nacelles) is analysed and the equating/values used in subsequent modules.

3. *Mass*

This module estimates the mass for each aircraft component using conventional project design methods, and adds them to determine empty, operational, zero-fuel and maximum aircraft weights:-

Aircraft Maximum T.O. Mass = Aircraft Zero-fuel Mass + Total fuel Mass
Aircraft Zero-fuel Mass = Aircraft Operational Empty Mass + Payload
Aircraft Operation Empty Mass = Aircraft Empty Mass + Operational Mass + Crew mass
Aircraft Empty Mass = Sum of all the aircraft 'structural' component Masses
= Wing + Fuselage + Nacelle + Empennage
+ Propulsion group + Undercarriage
+ Surface controls + Systems + Furnishings

Factors are included to each component mass to allow for technological changes not reflected in the estimating equations (e.g. introduction of composite materials).

The mass module also includes a section to evaluate the structural load factors (n) from the airworthiness requirements.

4. *C.G and Balance*

Two specimen loading cases are analysed to predict aircraft centre of gravity positions:-

The forward c.g. position is selected from:-

1. Empty aircraft position
2. Zero-fuel condition with payload evenly distributed in cabin
3. Simplified window-seating rule (forward seats only)

The aft c.g. position is selected from:-

1. Empty aircraft position
2. Aircraft at MTO with 20% payload at rear of cabin (rear luggage hold)
3. Simplified window-seating rule (rear seats only)

It is recognised that these cases are arbitrary but they represent current practice. Greater knowledge on the position of baggage holds and the interior layout would be required if more detail was to be included in the estimation.

The forward position is used in the estimation of field performance and the aft position is used in the valuation of the stability constraint.

5. *Aerodynamics*

Traditional aircraft project design methods have been used for the estimation of:-

(i) *Zero-lift drag*: from the summation of each aircraft component, plus factors to account for interference effects,

(ii) *Aircraft lift* : by considering the aircraft-less-tail, and adding the influence on lift due to the tailplane (by the summation of each aircraft component),

(iii) *Lift-induced drag*: by the summation of effects from each component,

(iv) *Compressibility effects:* using relationships developed at RAE.

Total lift and drag are determined at each flight condition and a complete lift/drag polar predicted for the aircraft and output in the result section.

The influence of flaps is treated in a separate sections (subroutine FLAP1, FLAP2). Several different types of flap are optionally available in the program:-

IFLAP	1 = Single slotted with simple hinge
	2 = Double slotted with simple hinge
	3 = Single slotted with Flower movement
	4 = Double slotted with Fowler movement

All the aerodynamic estimates were checked against known lift/drag polars for existing commuter aircraft and were found to predict values within acceptable accuracy.

6. *Stability*

The program predicts simple longitudinal stability criterion to check the static margin constraints. The stability constraint is used to position the wing relative to the fuselage and to size the tailplane for optimum configuration.

The static margin for the aircraft at the datum c.g. position (half loaded) is also evaluated and quoted in the output results.

7. *Engine*

Engine performance data for the General Electric/Garrett CFE 738 engine and the Rolls Royce/Allison RB 580 engine is included in a series of data block. This data is curve fitted where possible to simulate continuous functions for thrust and fuel flow. The interpretation of engine data represented a major difficulty in the work. A full description is included in Appendix section C7.

To allow for anticipated engine developments an overall engine scaling factor is included. In latter stages this parameter was treated as a design variable to obtain the optimum engine/airframe combination.

8. *Peformance*

Both 'aircraft flight profile' and 'field' performance parameters are estimated. The methods are typical of conventional aircraft project design.

Flight profile analysis considers the aircraft in three separate segments (climb, cruise and descent). Climb and descent are considered by analysing a series of equal height steps. Cruise is analysed by a series of equal distance steps. Restrictions on descent rates are checked to account for cabin re-pressurisation.

The program can handle multi-stage flight (of equal length) although in most of the studies a single stage profile was used.

The field performance estimates include:-

(i) balanced field length
(ii) landing field length
(iii) second segment climb gradient
(iv) WAT performance.

9. *Cost*

Estimation of cost is based on several standard cost procedures. Four sections are considered in the program:-

(i) *Standing charges* which include depreciation of capital, insurance and interest charges.

(ii) *Maintenance costs* for airframe and engine components, plus a cost associated with the maintenance burden.

(iii) *Flight costs* which include crew cost, fuel and oil useage, landing and navigation fees.

(iv) *Cost parameters* link the costs estimated above into conventional definitions:-

(a) DOC per flight

(b) DOC per mile

(c) Seat mile cost.

10 *Output*

There are nine pages of output.

The initial section lists all the input variables and constraints, their starting values and all controls.

The main body of the output report gives a detailed description of the optimised aircraft including:-

(i) geometric details

(ii) mass statement (including load factors and c.g. positions)

(iii) aerodynamic data (including the drag breakdown, drag polar, flap details and stability analysis)

(iv) flight profile analysis (climb, cruise and descent)

(v) field performance (BLF, LFL, and WAT)

(vi) cost estimation (aircraft price and DOC)

The final section lists the optimiser output parameters including the final design point, nature of constraints, convergence criterion, tolerance and warning messages (when appropriate).

A specimen output is shown in appendix F

4.5 Description of the PERI-OPT option

The original RAE optimisation program only provided output showing the final design point (the optimum) and the derivatives of each of the design variables with respect to the objective function at the design point. This derivative data indicates the sensitivity of each variable but it is difficult to interpret as an aid to design. Many designers require a "feel" for the design surface so that aspects influencing the design which have not been possible to include in the quantitive optimisation model can be considered. Such influences may push the design point away from the optimum. The designer wishes to know what flexibility exists in his choice around the optimum point.

The PERI-OPT program is an addition to the RQPMIN program which allows the designer to view the design surface around the optimum point. Although slightly inaccurate, it represents a substantial improvement in presentation of information to the designer. The program executive has been modified to allow the program to be run as a conventional optimiser or to call-up the PERI-OPT display.

The PERI-OPT program is activated after the optimiser has successfully identified an optimum design point. Any two of the design variables of RQPMIN can be selected for investigation. A window on the design surface which spans 15% each side of both design variables is opened. The 'single-pass' facility of the design synthesis module is used to generate a set of aircraft design points around the optimum. A 20x20 grid with the optimum value at the centre is produced (figure 4.7). Each of the following output parameters is evaluated at each grid point:-

1. Fuel mass (Kg)
2. Empty mass (Kg)
3. Direct operating costs ($)
4. Seat-mile costs (cents)
5. Wing mass (Kg)
6. Wing mass + Fuel mass (Kg)
7. Cruise Mach No.
8. Balanced field length (m)
9. Landing field length (m)
10. Static margin
11. WAT climb gradient

A contour plotting program developed at Loughborough[6] to map engine test data has been incorporated into PERI-OPT. The method involves scanning the 400 values of the output parameter to determine the maximum and minimum values. These two values are then displayed to the user and a request made for the number of intervals (contours) to be plotted between these values. The contour plotting routine selects each interval value in turn and searches the data to trace the appropriate contour. The trace strategy involves moving along the boundary coordinates until two values bracket the contour value. The trace is then started by determining the starting point by linear interpolation of these values. The adjacent box is divided by averaging the four corner points (ABCD) and assuming this value as the centre point (E), (figure 4.8). Each diagonal is interrogated clockwise to determine, again by linear interpretation, the exit point from the triangle ABE. The adjacent triangle is then made active and interrogated in the same manner. The procedure is continued into new boxes (figure 4.9) until the trace reaches a boundary or it rejoins the starting trace point. The method is repeated for the same output parameter contour value and then sequentially through all contour values until all traces have been identified.

Graph plotting involves conventional routines (GINO) held in the computer library. Plots may be obtained of any output parameter contours. Specimen output is shown in figure 4.10. It is possible to produce a compilation of contours from several parameter runs as shown in figure 4.11. A full discussion of the results of the PERI-OPT option is given in section 5.1.4 which also includes a full set of plots for a particular study.

It should be appreciated that the surface that is displayed by this process is not the true design surface searched by the optimiser. It represents only an approximation to this surface. The discrepancy arises due to holding all the design variables at their optimum values (except for those under investigation) and performing only a single-pass analysis through the synthesis module. For example, reducing the wing aspect ratio would alter the aircraft climb performance and this in turn would change fuel requirements for the specified range. Also, changes to the aircraft wing area will directly alter the maximum take-off mass. It would be impossible to determine the true surface at each of the 400 data points because many of them lie in unfeasible regions and the optimiser is not able to proceed with the search method until a step is made into a feasible region.

The PERI-OPT program was substantially revised to utilise the new graphics software available on the new university Hewlett Packard mainframe computer. The UNIRAS program replaced the GINO, GINO-GRAPH and the contour plotting routines.

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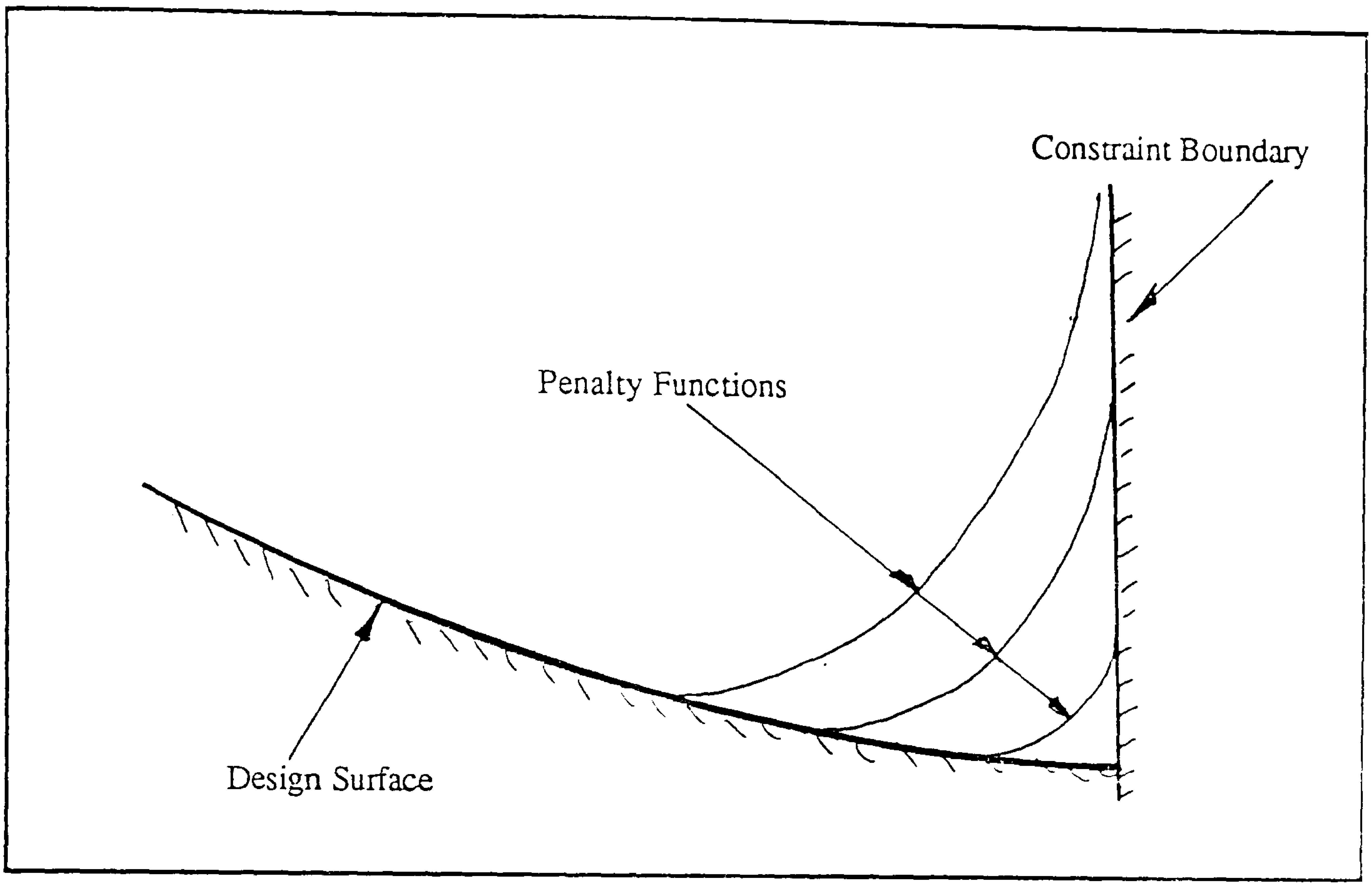


Figure 4.1 Constraint Boundaries

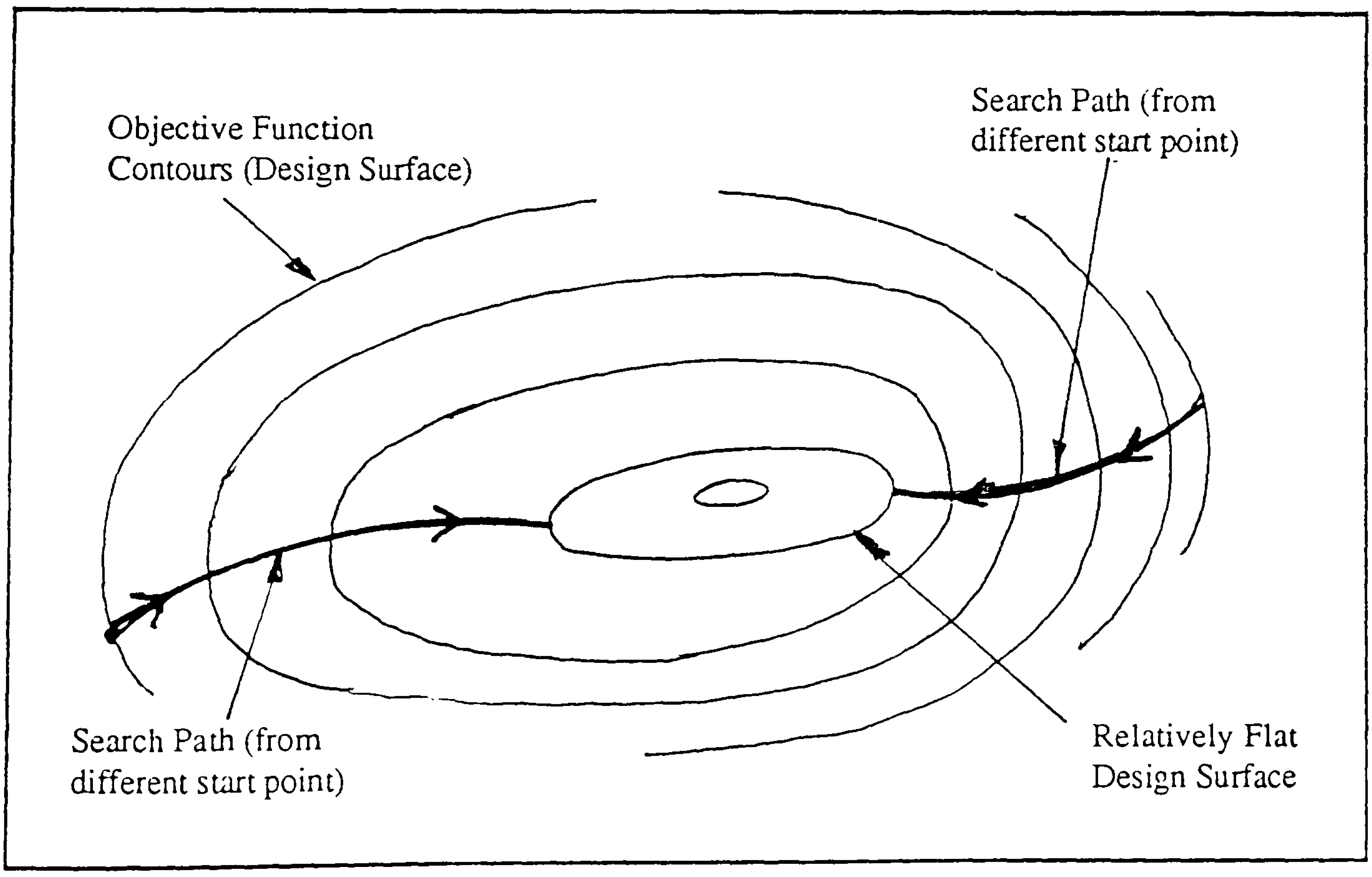


Figure 4.2 Objective Function Tolerance

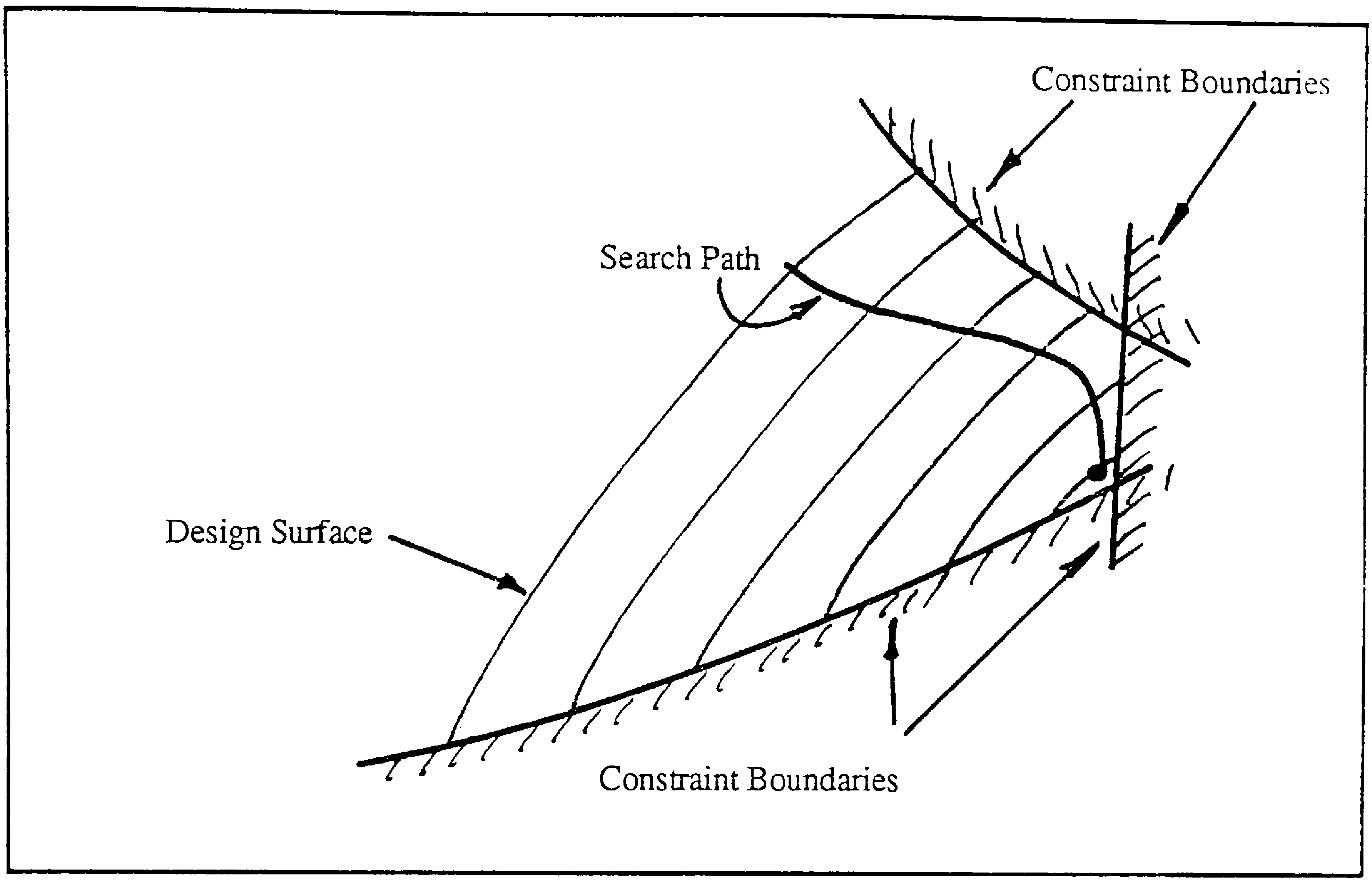


Figure 4.3 Search Progress Interrupted by Constraints

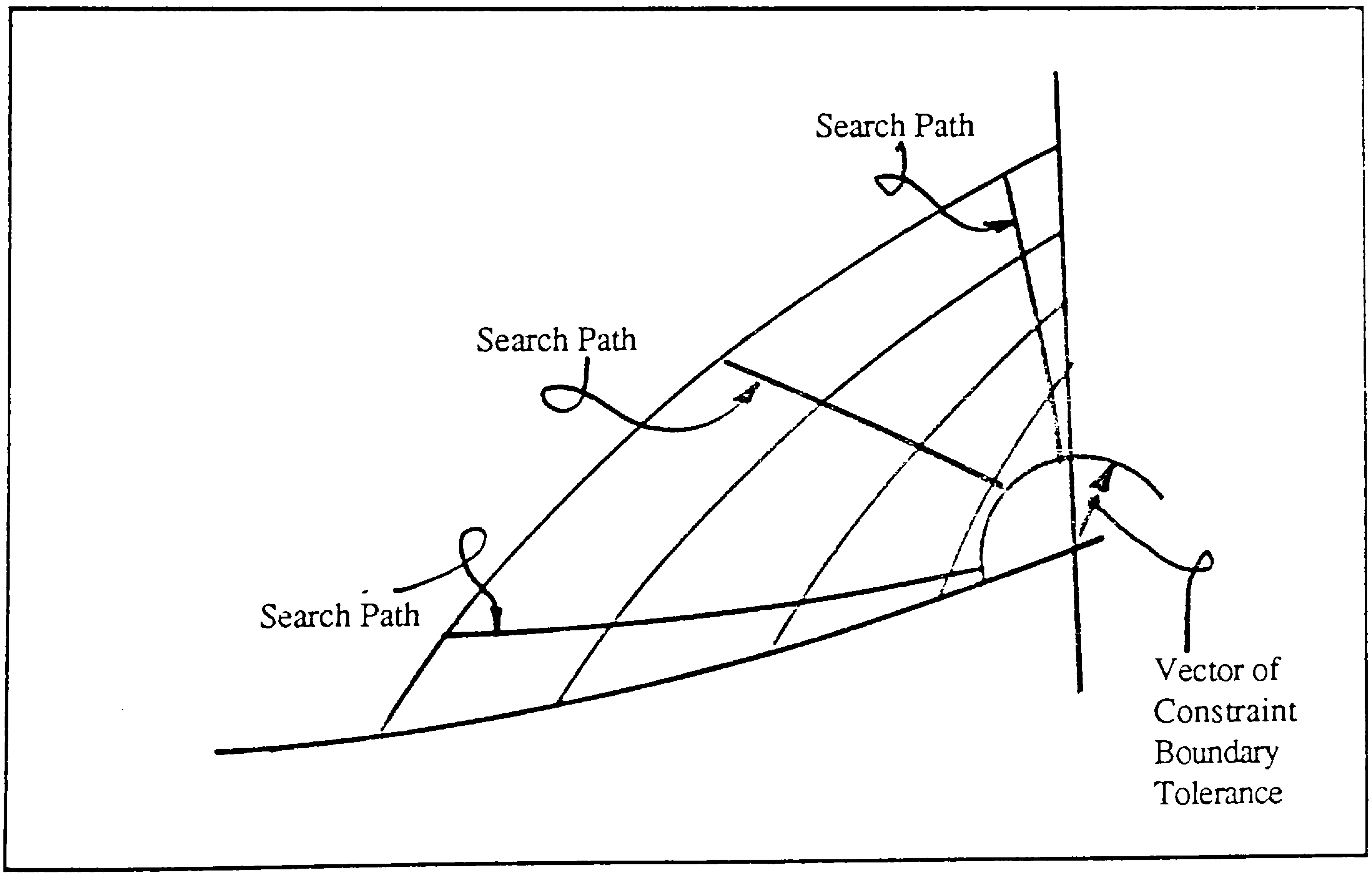


Figure 4.4 Constraint boundary Tolerance

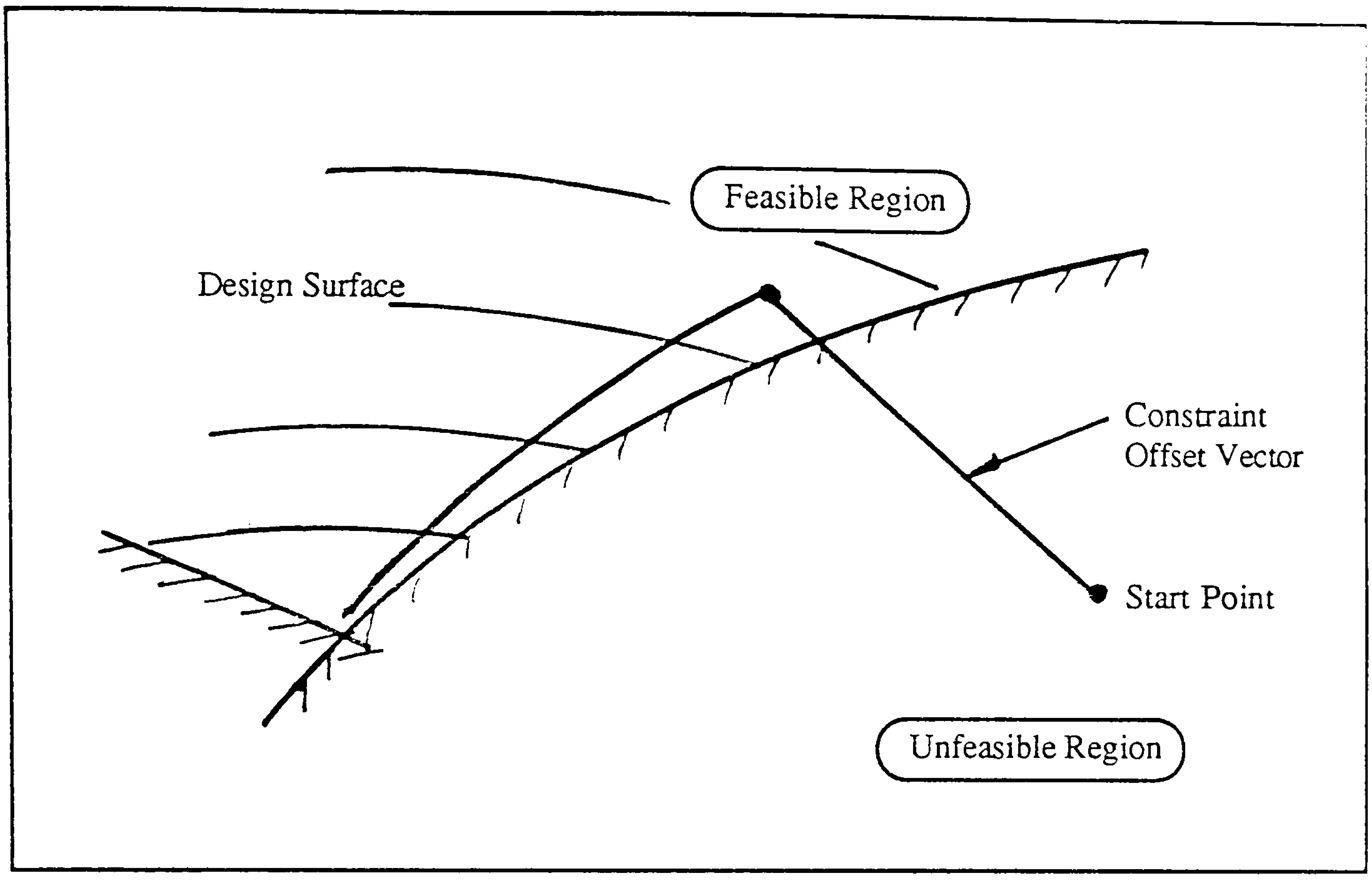
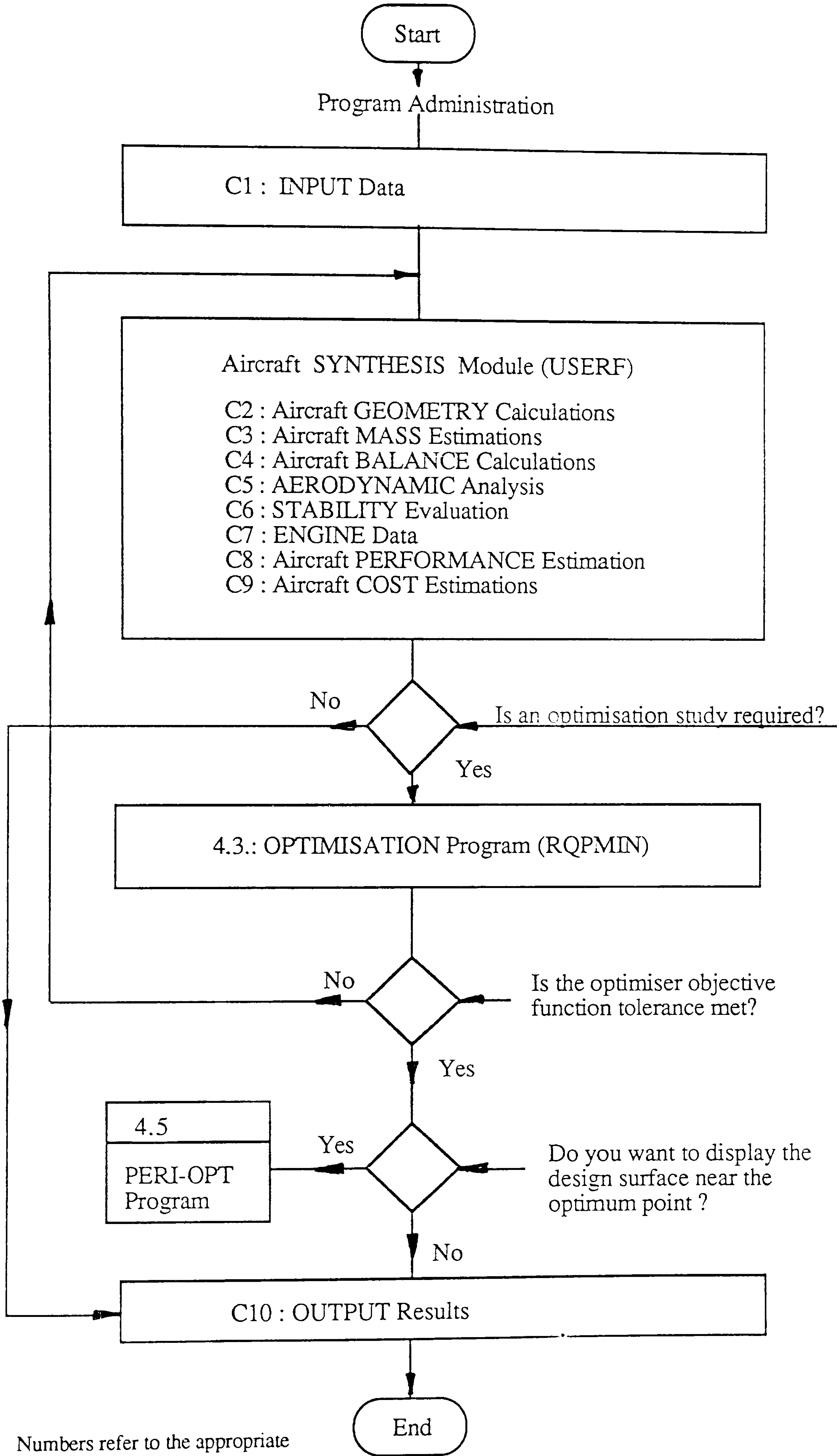


Figure 4.5 Feasibility Step



Numbers refer to the appropriate section in chapter 4 and appendix C.

Figure 4.6 Program Architecture

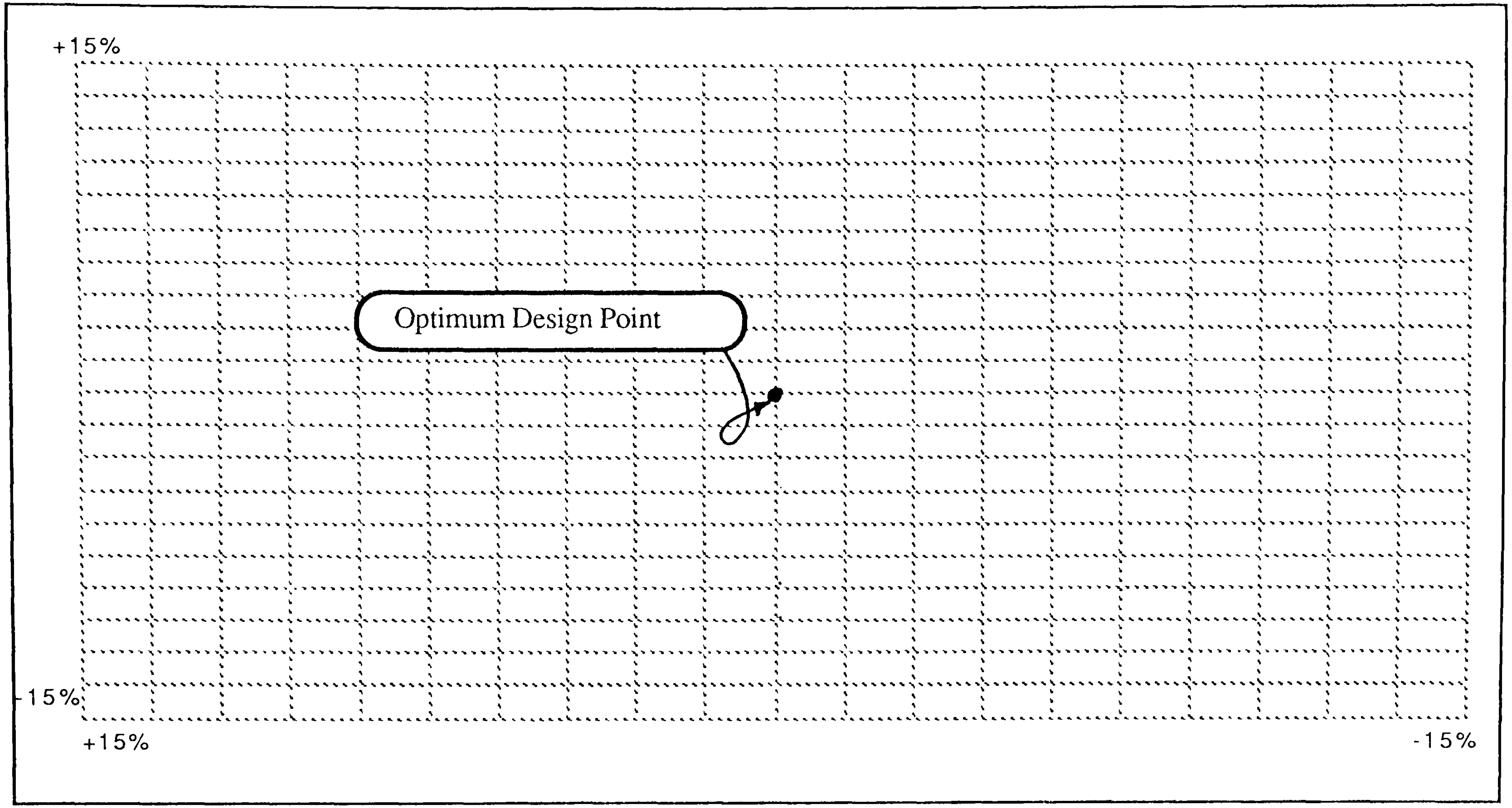


Figure 4.7 PERI-OPT Grid Description

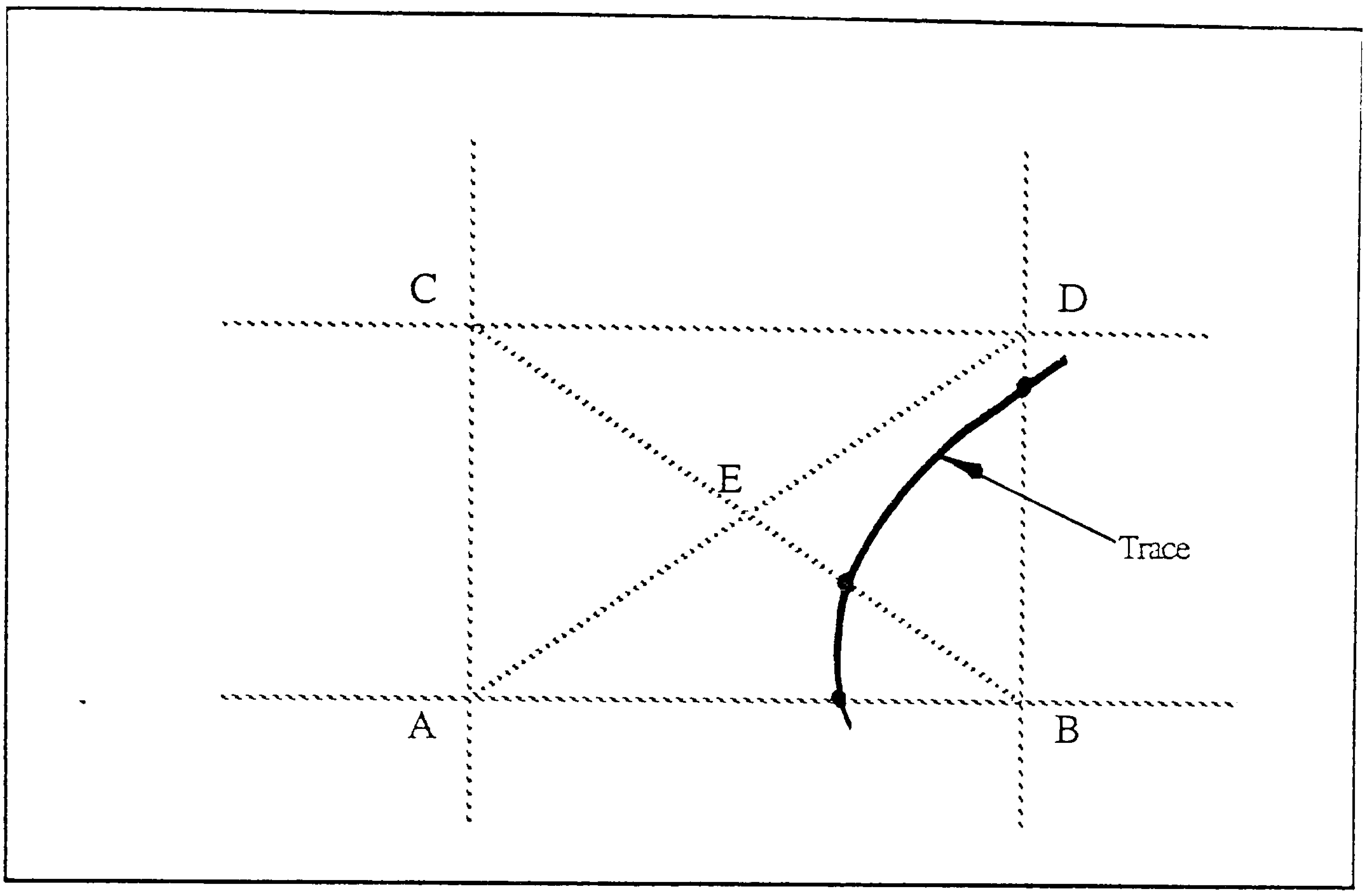


Figure 4.8 Contour/Trace Plotting Strategy

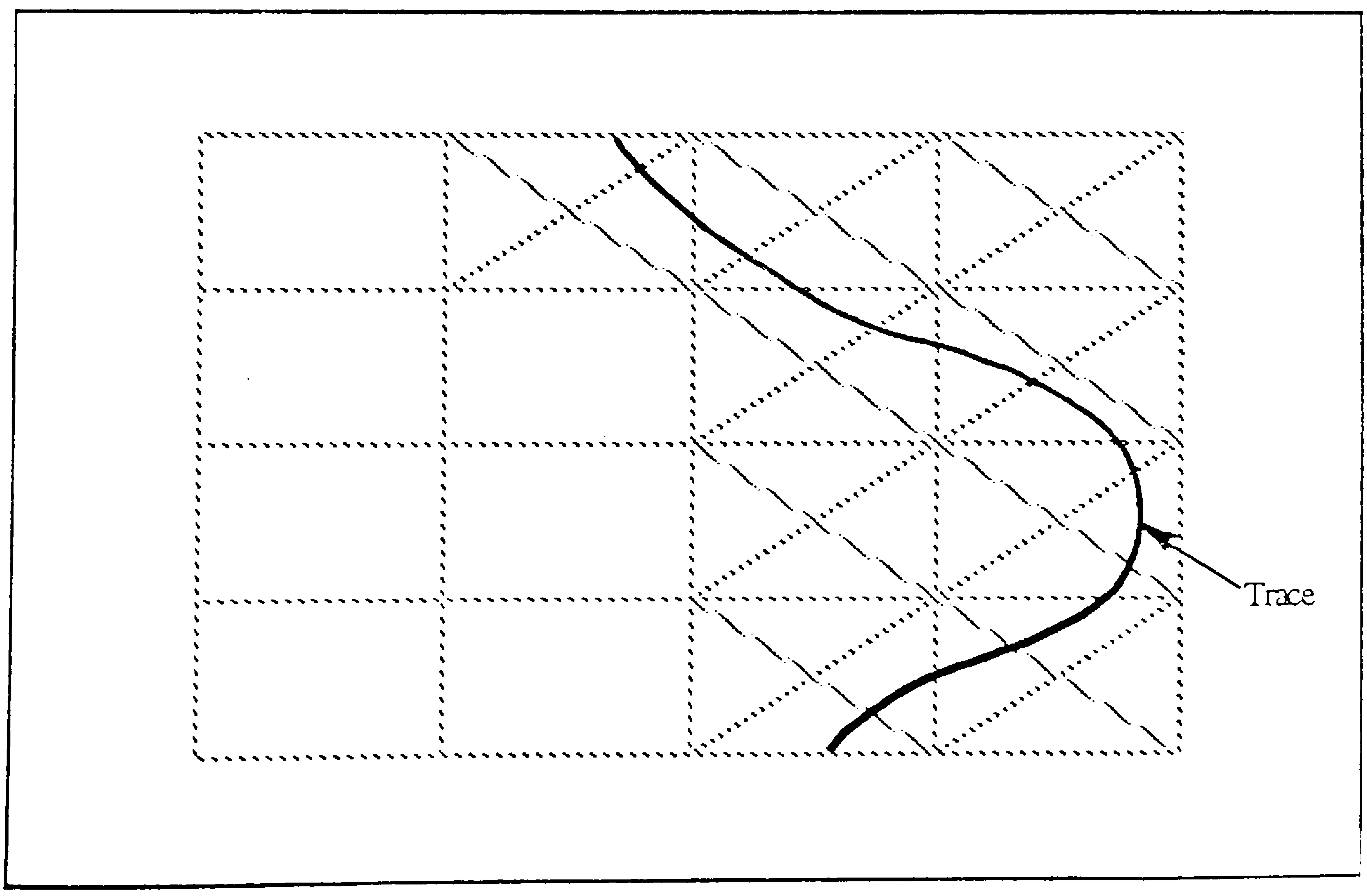


Figure 4.9 Trace Path Across Grid

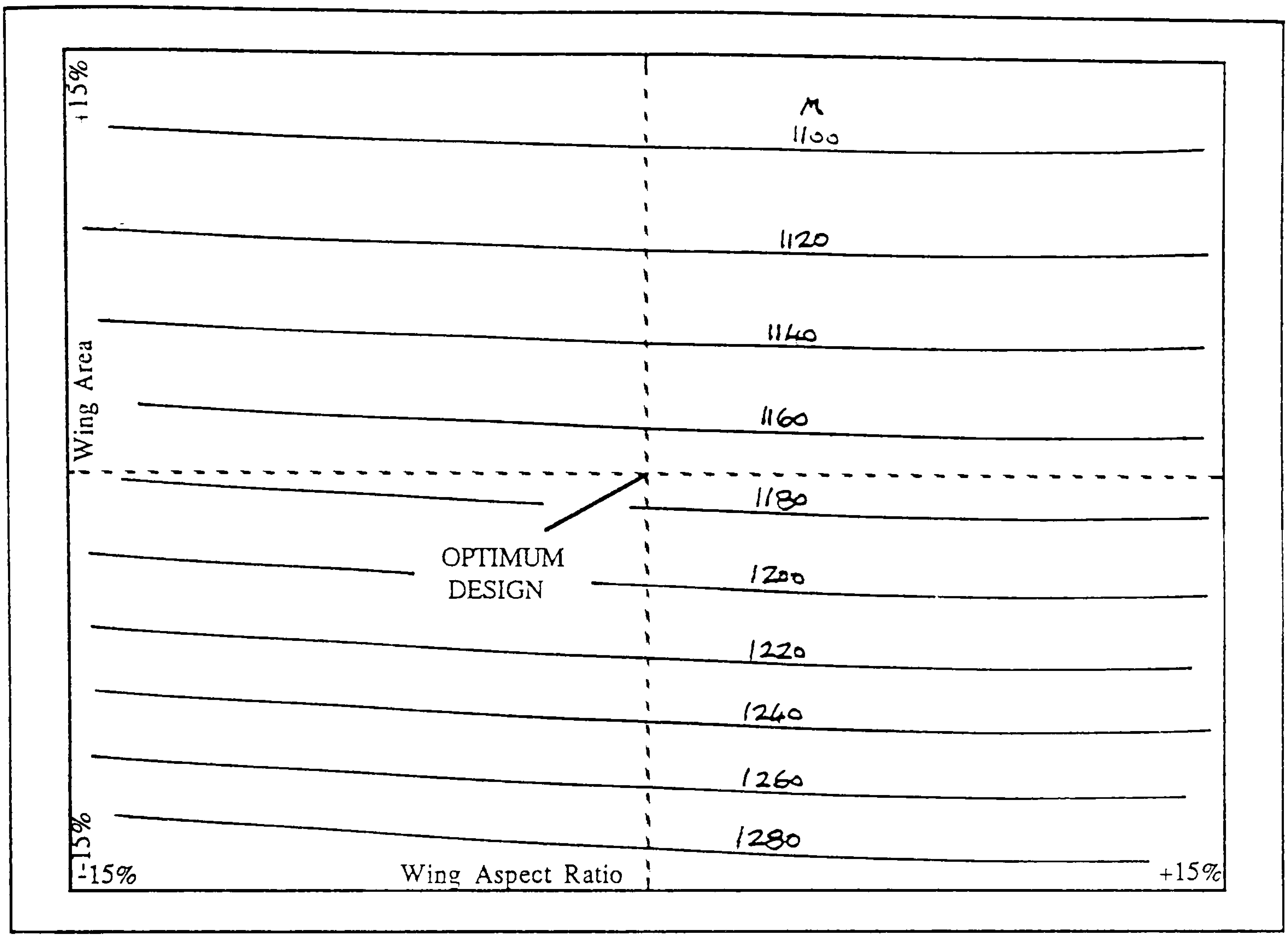


Figure 4.10 (sheet 1) PERI-OPT Parameter Plot (BFL)

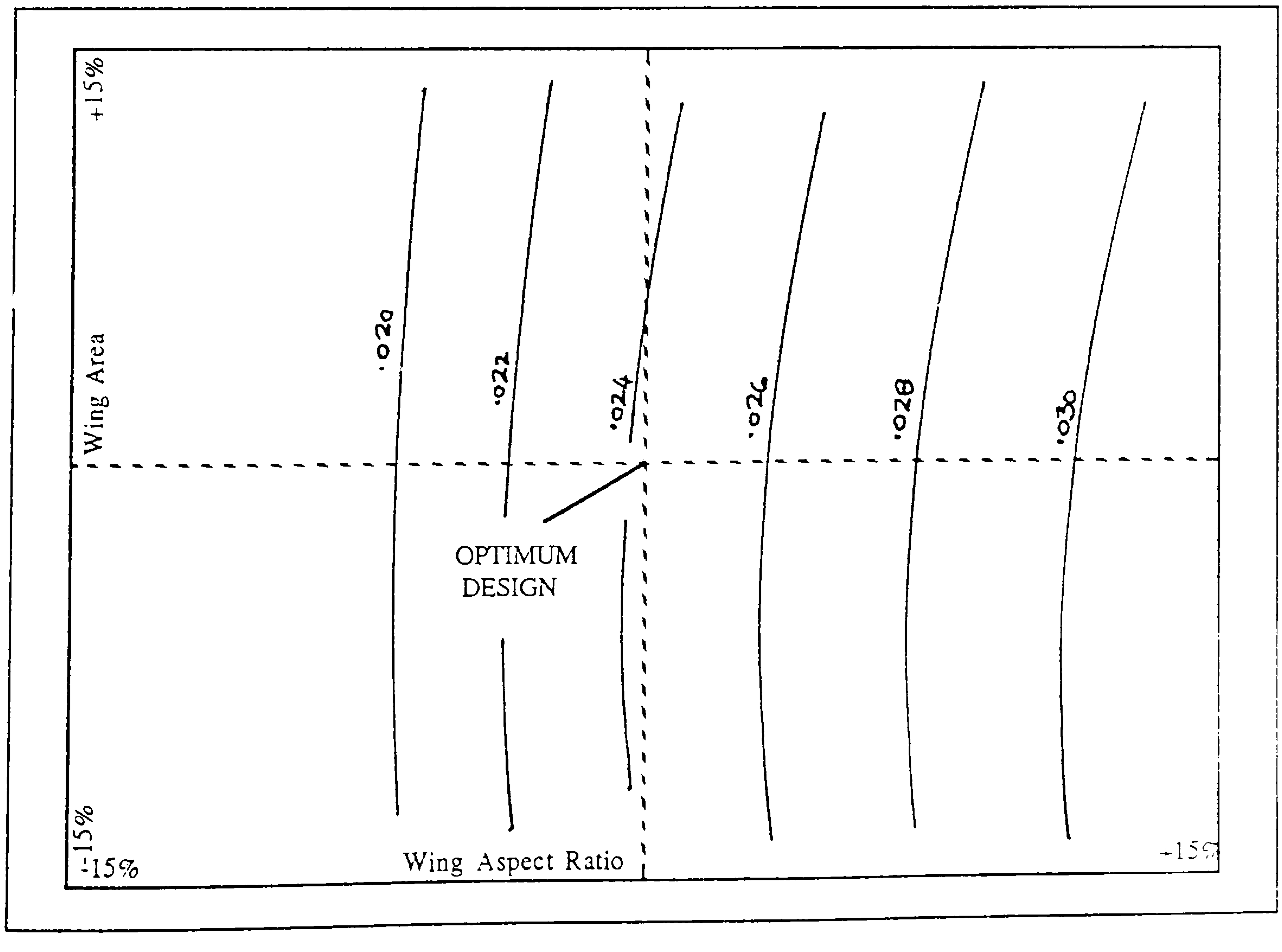


Figure 4.10 (sheet 2) PERI-OPT Parameter Plot (WAT Grad)

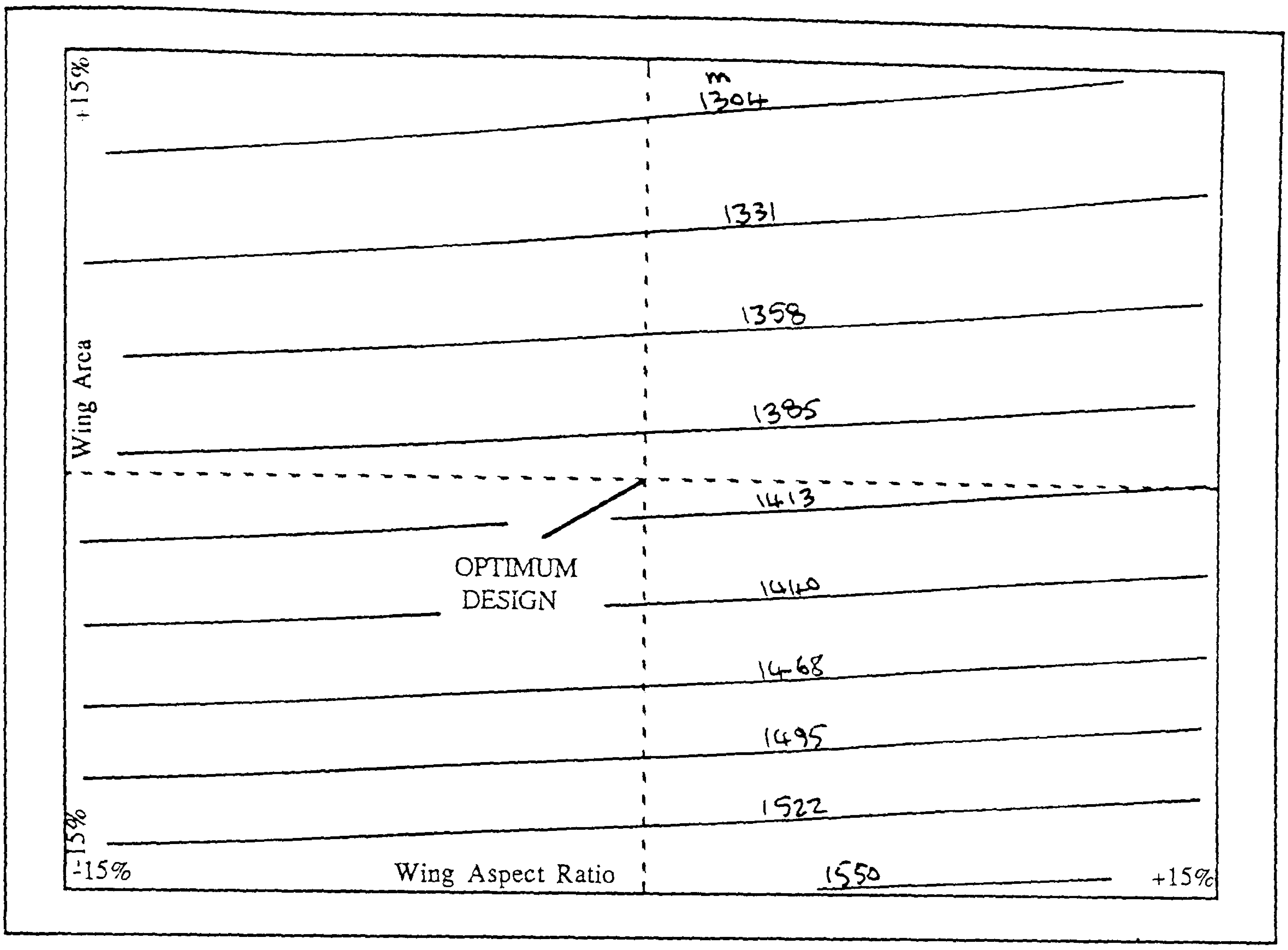


Figure 4.10 (sheet 3) PERI-OPT Parameter Plot (LFL)

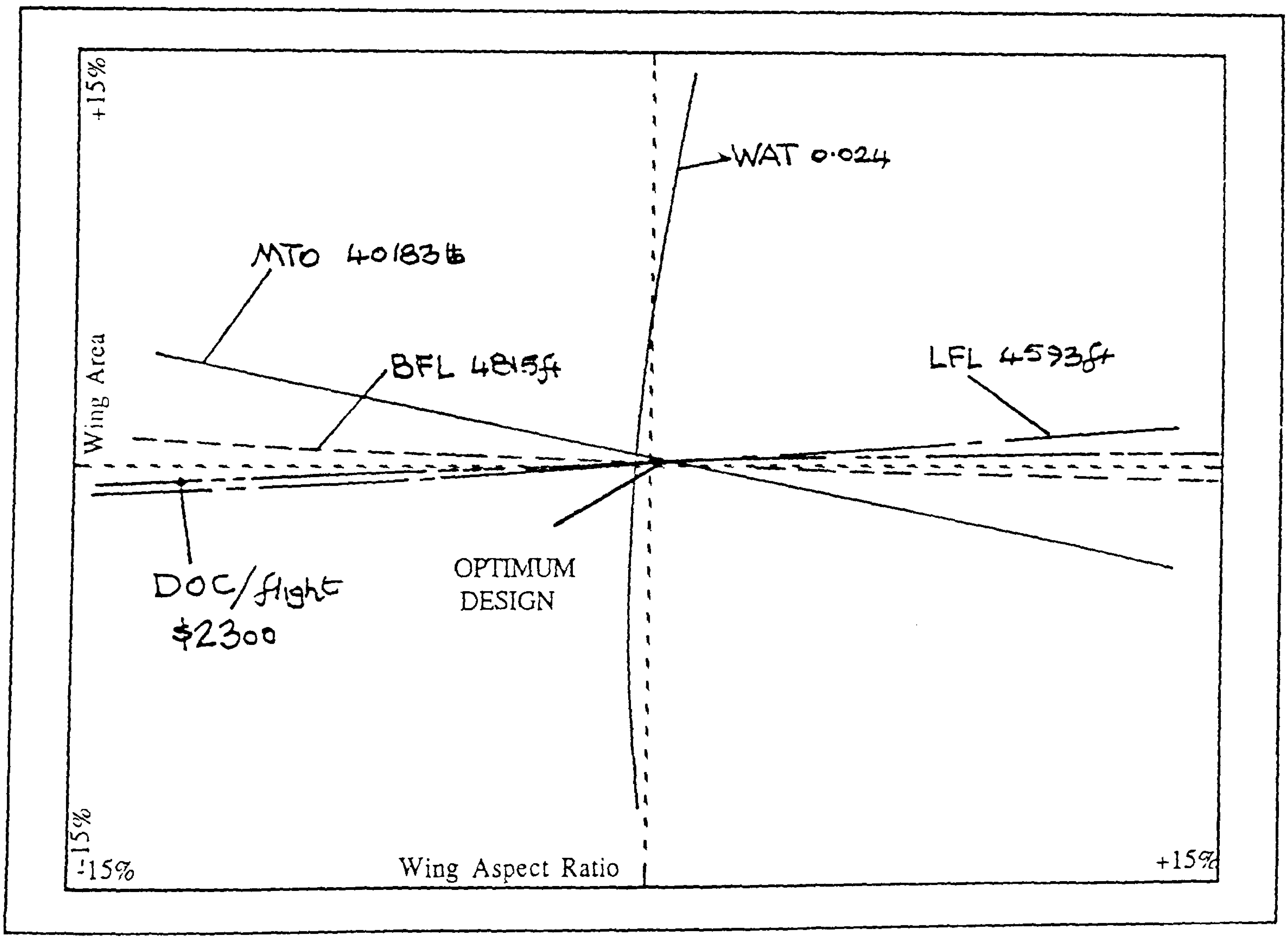


Figure 4.11 PERI-OPT Parameter slopes at optimum point.

Chapter 5

DETAIL DESIGN STUDIES

Initial project design always presents difficult decision areas to the designers. Once a particular aircraft configuration has been finalised it is too expensive to introduce major changes, therefore there is considerable pressure on the design team to 'get it right'. The situation is further complicated by the changing technical and commercial environment surrounding the design. Improvement in engine performance, new airframe and aircraft systems technology, the emergence of new competitor aircraft and the changing operational and regulatory framework are only some of the possibilities for change. The designers are not only concerned with the specification of the initial design but also the strategy for future aircraft development. This is likely to include the choice of engine types and the aircraft stretch capability. The initial design is therefore unlikely to be exactly matched to the initial operational specification but it must not be compromised to an extent that the design is uncompetitive. It is within this context that the value of the optimum design method should be judged.

The industrial environment, in which the design team works, places strong emphasis on component design aspects. These are pursued in fine detail and constitute substantial technical effort. Past experience has shown that careful control of the aircraft detail design in the early stages offers the best method of avoiding technical difficulties later in the design cycle. The broader based optimisation studies can be considered as complementary to this detail design effort. Together they provide both micro and macro design senarios which help the designer in this difficult choice of initial aircraft specification and in subsequent developments.

In the early stages of the design, when the aircraft geometry and performance criteria have not been fixed, the optimisation studies are used to identify the absolute 'best' configuration with respect to various operational specifications. This enables the designers to judge the sensitivity of the design with respect to variations of the aircraft performance parameters. Once the baseline design has been established the optimisation studies are used to evaluate the tolerance available in the selection of wing geometry parameters. More particular goemetrical features (e.g. rear-engine position) can also be assessed to show the quantifiable penalties/benefits of the proposal.

Design studies conducted in this early phase can also be used to evaluate the potential for the initial aircraft stretch. In this case optimisation studies can be used to show the limitations on the design imposed by the proposed engine performance and the interrelationships that exist between engine and airframe parameters.

The optimisation methods can also be arranged to reveal the strengths and weaknesses of competitor aircraft in comparison with the baseline aircraft.

For the FJX design, the optimisation studies influenced this process by:-

(a) confirming the advantage of a small increase in wing aspect ratio,
(b) confirming the advantage of a slightly larger than optimum wing area,
(c) confirming the choice of engine position,
(d) indicating the advantage of stretch to 44 or 48 seats,
(e) indicating the restrictions imposed by the engine power limitations,
(f) identifying the pros and cons of a competitor aircraft (Challenger RJ).

After the initial design has been finalised, significant changes to the configuration are no longer considered. The project designers are then concerned with design opportunities from alternative engines and the potential for aircraft stretch. Such considerations formed a series of optimisations which were conducted nearly a year after the initial studies. In the intervening period the FJX design had included the detail changes described above, the CFE engine performance had been improved and the aircraft design was publicly displayed at Farnborough (1988). Within the limitations of the available flap system and an acceptable approach speed, the aircraft stretch studies were mainly concerned with the trade-off between engine power and wing area increases. The choice of specific increases in aircraft size (44/56/68 seats) were made to set the new designs in different operational/competitive markets.

Such studies clearly show the limitations of engine scaling and thereby the suitability of particular engines. Simulation of different makes of engine is also feasible in this type of analysis. This allows the comparison of available engines to be made within the total aircraft design. Improvements to the basic configuration of the aircraft (e.g. change of flap type) can also be investigated to show the trade-off between different aircraft options (i.e. wing area versus power increases). Later in the development of the aircraft design such studies can be related to particular engine development. In the case of the FJX aircraft the earlier work had shown the advantages of using a more powerful engine than the originally preferred CFE type. In these later studies there are advantages in changing the method of analysis to align the engine scales to values associated with projected engine developments. These studies can simulate the near- and far-term engine improvements to show how the aircraft could be stretched. The FJX studies clearly showed the advantages of over-winging and over-powering the initial design so that the first aircraft stretch could be accomplished with only small modifications to the initial configuration.

The particular investigations conducted in the type of study described above raises the general question of what was the optimum relationship between aircraft and engine changes. Such relationships, although not directly applicable to 'real' aircraft configurations, due to compromises faced by the design team, do provide the designer with a knowledge of the absolute 'best' design surface. This allows him to judge the 'penalties' inherent in his chosen configuration. Such generalised design studies provide a theoretical framework for future designs and offer a methodology which can also be useful in the teaching of aircraft project design.

Introduction to the design studies

The design and optimisation methods described in the previous chapter (4) and appendix C have been used in a series of design studies which follow a similar pattern to that described above. It is convenient to consider these in two separate sections:-

5.1 Industrially Related Studies
5.2 Generalised Design Studies

In the first, a programme of interrelated aircraft project design studies was undertaken in association with Short Brothers (Belfast) as part of their FJX design and development programme in 1986-88.

In the second, the computer design method was used to generate a series of generalised design curves which illustrate the sensitivity of design parameters that are significant for turbo-fan commuter aircraft design in the 40 to 80 seat size.

Both types of study are useful with respect to different design tasks, either as a comparison with actual designs (to show the variability of the actual design from the optimum and the influence exerted by the principal design parameters), or to define the design surface so that a rational choice of design point can be made. In these ways the method is used as an aid to the overall project design task.

All the aircraft that are created by the method are optimum designs. There may be many reasons why the actual aircraft specification is chosen away from the optimum point. For example, only those aspects of the design which are quantifiable in terms of the design variables can be optimised and the designer will have to consider many other design parameters when selecting the final specification for the design.

The studies described below are selected to illustrate the type of design information which will assist the designer in such choices.

Individual summaries of the detail design aspects highlighted by specific studies are included at the end of the appropriate section. A general discussion of the method is presented in the next chapter.

Although the synthesis model is written in SI units and all calculations in the program are done in this system of units, the output of the early studies (section 5.1) was intended for industrial cooperation where the old Imperial system of units still dominate. The hard-copy computer printout was modified to provide values in both sets of units. To avoid duplication, the condensed versions of this data (tables and diagrams), presented in the following sections are compiled in Imperial units only. The tables and diagrams associated with the generalised studies (section 5.2) are also reproduced in Imperial units only, to provide consistency in presentation.

5.1 Industrial Related Design Studies

These studies can be considered in four phases (in chronological order):-

(1) Initial 40 seat designs incorporating the CFE engine and an analysis of a competitor aircraft (Canadair Challenger)
(2) FJX developments (44 seats)
(3) FJX/RR stretched designs (56-80 seats)
(4) A PERI-OPT study

A brief introduction of the background to this work is appropriate before the detailed description of the studies is presented:-

Recognising the need to extend the range of commuter aircraft around the 30-36 seat designs which had been successfully sold for the previous ten years, Shorts decided to investigate the 12-30 seat and the 36-50 seat market for turbo-prop aircraft. Two of the main influences that were identified were the anticipated strong demand for commuter-type aircraft throughout the next twenty years, and the increasing expectations of passengers for fast, quiet and 'modern' designs.

At the same time as the Shorts work was progressing, engine manufacturers were identifying an increase in demand for jet-executive travel. Many of the engine companies responded by proposing new designs (or developments of existing types) in the 6000 lb T.O. thrust size. One of the first engines to be announced was from the collaborating General Electric/Garrett companies. The joint venture engine, designated CFE 738, combined the central HP compressor, combustor, HP turbine and fuel systems from the GE27 turbo-shaft engine with a new fan and LP turbine from Garrett. With an overall bypass ratio of 5.3, the engine produced 5600 lb.T.O. thrust (SL) at a cruise sfc of 0.65 lb/lb/hr. When these engine details were released, Shorts were projecting a 40 seat turbo-prop aircraft. They decided to investigate the re-engining of this project to suit the new turbo-fan engine. Rear engine position was still in contention at this time for the turbo-prop layout and this made the turbo-fan aircraft configuration uncertain. The first phase of the optimisation studies preceded the initial definition of the FJX aircraft and were used as parametric studies for geometry and mission definitions. These baseline design sensitivity studies were used to confirm the initial FJX layout.

The second phase of the work was used as a simulation of the FJX design which by this time was well defined. In these studies it was possible to show the design trade-offs in detail. Although engine thrust developments were not finalised at this stage, Shorts were interested in the stretch potential of the aircraft and the implications of engine improvement. During this stage a new Rolls Royce engine (RB 580) was announced. This engine offered higher initial thrust and more thrust development than that possible from the original CFE design.

By the third phase, the RR engine had fully emerged and it was clear that the existing 44 seat design could be easily stretched to 56 seats with the launch engine. Future (projected) increases in engine power offered various options for aircraft sizing and these were investigated.

Each of the three phases is now described in detail.

5.1.1 INITIAL STUDIES

The earlier turbo-prop design studies[1] had concentrated on the larger size (30-50) seat aircraft. Initial work on the turbo-fan designs showed that it would be difficult to economically compete with aircraft smaller than this band. The 40 seat aircraft was regarded as the minimum size but with the intention to stretch to larger sizes. Market analysis[2] suggested that 70-80 seat aircraft were financially more attractive to the company but it was felt that competition may arise from de-scaled existing 100 seat designs. The design strategy was therefore settled as starting small (about 40) and extending to the larger size as engine thrust developed.

At the start of the programme only the cabin diameter (recommended in a separate configurational design study[3]) and the engine type (CFE) were fixed parameters. The choice of mission (stage distance and field length), wing geometry and engine position (wing or rear fuselage mounting) were uncertain. The optimisation studies were used to assist in these choices.

The earlier turbo-prop aircraft synthesis module was modified:-

- Turbo-fan engine performance subroutines added
- fuselage mass (increased to allow for pressurisation).
- tail surface mass (reduced to reflect the adoption of composite materials).
- landing gear (increased to typical jet aircraft standard).
- APU mass (350 lb) added to system mass.
- fuel allowance of 100 lb per stage added (to account for ground and near-ground manoeuvres).
- fuselage repressurisation rate introduced (to restrict the rate of descent).
- engine emergency boost setting (+ 11%) added to single-engine performance estimations.
- engine scaling factor added.
- cruise Mach number limited to 0.75 (later increased to 0.85)
- fuel priced at $0.75 per US Gal.

- at the same time the original cost method was modified to reflect the Shorts cost estimation method. All these changes are included in the description of the program (chapter 4) and appendix C

Apart from the fuselage and engine details the following items of the aircraft specification were fixed in the initial studies:-

- flap-type (single-slotted Fowler)
- WAT specification (+ 25°C ISA-SL)
- BFL limit set at 5300 ft
- Stage length 1000 nm (single stage)

A summary of each study in this section is shown in figure 5.1 and the detailed results can be found in appendix D (figures D1-9) for each study.

The first optimisation was performed with maximum LFL (Landing field length) equal to maximum BFL (Balanced field length) and set at 5300 ft. The results are shown in figure D1 (appendix D). Design 1 shows an aircraft with substantially less wing area and higher wing aspect ratio than the design under investigation by Shorts. Further detailed investigtions indicated that they were adopting a much more critical landing field length. In effect this may be considered as providing an inbuilt stretch capability for the aircraft, or an insurance against weight growth. To balance the optimum specification with the Shorts design, the LFL was restricted to 4660 ft in the next optimisation. The resulting aircraft configuration (Design 2) is similar to the company design (Design 3) and was therefore accepted as the baseline specification. The 'penalty' of including the stretch potential can be judged by comparing the two optimum aircraft. The first aircraft (with LFL = BFL) is seen to be significantly more efficient on all the technical counts. The baseline design carries the following penalties:-

+1.89% in aircraft max. take-off-mass
+3.45% on aircraft price
+3.72% on aircraft DOC per flight

The wing aspect ratio on Design 1 was set as a free variable. The value of 11.3 selected by the optimiser may present manufacturing and wing stiffness difficulties that have not been allowed for in the estimating model.
To show the influence of the engine emergency boost availability on the baseline design the next optimisation (Design 4) was conducted with this feature removed (EMBST = 1.0). A direct comparison with the baseline design shows that although the wing area is not substantially changed, the aspect ratio is increased to 11.8 to restore single-engine climb rates. This translates into penalities of:-

+1.93% on T.O. mass
+1.87% on Aircraft price
+0.76% on DOC/flight

Discounting the other penalties, the price increase of $176000 represents the value of the engine boost facility to the aircraft design (representing approximately 10% of the engine price).

Wing geometry

The optimum design of the baseline aircraft selected wing taper at the minimum value of 0.24 (i.e. max. permitted taper) and the wing thickness at 0.15 (i.e. max permitted thickness). To investigate the sensitivity of the design to the

selection of these values a series of optimisations was performed with taper and thickness at fixed values. The results are shown in figure D2 (appendix D) and some of the significant aircraft parameters are plotted in figure 5.2 (taper) and 5.3 (thickness). All the aircraft fixed parameters are similar to the baseline (Design 1). The study pattern is:-

Design	Taper Ratio	Thickness Ratio
1	0.24	0.15
2	0.30	0.15
3	0.35	0.15
4	0.24	0.13
5	0.24	0.11

Although taper ratio is seen to be less sensitive than thickness-chord ratio it still represents a significant change, over the range of values considered (0.24 to 0.35) viz:-

+2.37% on wing area
+1.06 % on T.O. mass
+1.16% on aircraft price
+0.93% on DOC/flight

Wing thickness is seen to be more influential in the selection of optimum design values, over the range of values considered (11 to 15% viz):-

-3.74% on wing area
-6.98% on aircraft empty mass
-4.28% on T.O. mass
-5.57% on aircraft price
-2.80% on DOC/flight

The only positive change is seen as the reduced drag effect for thinner sections. This is seen to save 2.93% on trip fuel. The study highlighted the desirability to select the maximum taper and thickest wing possible from aerodynamic, structural and manufacturing considerations. A taper ratio of 0.24 and an average wing thickness ratio of 0.15 were regarded by the company as the limits for future work. It must be recorded that the design model used did not, at this stage, include drag contributions from compressibility effects as the designers felt that these could be avoided if the maximum thickness limit was restricted to a maximum value of 15%.

In this series of optimisations the aspect ratio was included as a design variable. As taper ratio reduced,optimum aspect ratio was seen to be relatively insensitive (from 9.22 to 9.01). As thickness reduced, aspect ratio increased (from 9.22 to 10.34). Again wing thickness is seen to be more influential than taper. The aspect ratio/thickness variation is not compatible with wing stiffness requirements as the larger span designs are associated with a smaller structural wing box.

The strong influence of wing thickness on the optimum design, indicated the need to carefully model the effect of wing thickness in the synthesis program. Early RAE optimisation studies had suffered from an over-sensitive wing thickness influence on the design. With this in mind, the estimating model was analysed and compared to the more detailed estimations made at Shorts. The model was regarded as predicting with acceptable sensitivity.

Wing aspect ratio

The initial studies indicated the tendency of the optimiser to select high values for wing aspect ratio in order to improve climb gradients in critical BFL/WAT conditions. In these critical engine power/weight ratio cases, the aspect ratio is selected high in preference to other aircraft parameters. To investigate this effect a series of aircraft optimisations was conducted at fixed values of aspect ratio (10.5 to 7.5). The baseline specification was used in all cases. The results are shown in figure D3 (appendix D) and the optimum values for the significant aircraft parameters are plotted in figure 5.4. The design at AR = 7.5 is only just feasible but dictates a large wing area which degrades cruise performance, making it an uneconomic design. The absolute optimum value of aspect ratio is seen to be approximately 9.22 (confirming the prediction in the baseline study). Aspect ratios fixed below this value show large increase in all the plotted parameters. This is mainly due to the critical nature of WAT/BFL in the designs with lower than optimum aspect ratios. This effect forces an increase in wing area to meet the single-engine climb gradient. Aspect ratios values above the optimum are seen to have only a modest increase in DOC and wing area but larger increases in aircraft empty mass. This study shows the advantage of selecting an aspect ratio at about 9.0. The mass model did not, at this stage of development, account for aeroelastic stiffening effects (these were added later) but this omission was not regarded as significant for aspect ratio choice below a value of about 10.0.

Mission studies

The aircraft specification for the earlier studies used a single-stage profile (1000nm). The optimisation model could handle multi-stage missions but the results were compared with the detailed point design analysis done in parallel at Shorts and this industrial analysis was based on this single-stage profile. The optimiser multi-stage facility was used in a series of studies to show the influence of different flight profiles on the optimum design point. Three extra missions were investigated (each was felt to approximately equate to the original 1000 nm specification):-

(a) 4 stages of 200 nm
(b) 3 stages of 250 nm
(c) 2 stages of 400 nm
(b) 1 stage of 1000 nm

- for each mission two field specifications were considered:-

(i) BFL = 5300, LFL = 4660, AR = 9.0
(ii) BFL = LFL = 5300, AR free (7 min to 13 max)

The results are shown in figure D4 (appendix D).

The 4x200 mission is seen to be unfeasible for both field specifications. All the other studies gave acceptable designs. This indicates the critical nature of the engine power available from the CFE engine. As expected, all the multi-stage flights used substantially more fuel than the baseline specification. This was due to the saw-tooth profiles adopted (i.e. cruise segment distance set at minimum value and flown at lower altitude than the single stage mission), the increased proportion of the total time spent in the climb phase, and the addition of extra ground manoeuvre fuel.

Engine position

The earlier turbo-prop studies had shown the advantages of positioning the engines on the rear fuselage. Many of these advantages relate to the effects of the propeller and are not appropriate to turbo-fan engined aircraft. To investigate the effects of rear-engine installation on the baseline design two further optimisations were performed. The results are shown in figure D5 (appendix D).

Design	Description
1	Baseline design with AR = 9.0
2	Baseline design with AR free
3	As 1 with rear-engine layout
4	As 2 with rear-engine layout

The rear-engine installation is seen to increase the fuselage mass, shorten the tail arm (thereby increasing tail areas and masses), and increase wing mass (due to reduced wing weight relief). Together with other changes, the baseline aircraft T.O. mass is increased by 3123 lb (8%). This forces a substantial (126 sq.ft = 22%) increase in wing area to meet the single-engine climb requirement. The extra drag reduces cruise speed which increases block time by 487 sec (6%) and hence seat mile cost by 10%. Allowing wing aspect ratio to increase and relaxing the LFL requirement brought the wing area increases down to 40 sq.ft (7%) with the aspect ratio raising to 10.41. In this case the rear engine layout is still 5.5% heavier and with 4% increase in DOC. Although the study methods may be regarded as assessing these configurational changes too critically, it does show that the rear-engine position leads to significantly less efficient designs for this type of turbo-fan aircraft. This effect may be more pronounced in those designs in which engine power is marginal. The results confirm the importance of weight control in the baseline design. A study of the Canadair Regional Jet (see below), which is regarded as considerably overpowered for the 48 seat design did not exhibit such large penalties.

Aircraft stretch

Although the baseline optimisation studies showed that the available CFE engine was well matched to the 40 seat baseline aircraft specification, the relationship between engine and aircraft stretch was of interest. One and two seat row extensions to the fuselage cabin were considered (44 and 48 seats) with a range of fixed engine scales:-

Design	Description
1	44 seat, Engine Scale 1.0, AR = 9.0
2	As 1 with AR free
3	44 seats, Engine Scale 1.10, AR = 9.0
4	44 seats, Engine Scale 1.15, AR = 9.0
5	48 seats, Engine Scale 1.10, AR = 9.0
6	48 seats, Engine Scale 1.15, AR = 9.0
7	48 seats, Engine Scale 1.20, AR = 9.0
8	48 seats, Engine Scale 1.25, AR = 9.0

The results of the optimisations are shown in figure D6 (appendix D) and some aircraft parameters are plotted in figure 5.5. All these designs had maximum LFL set equal to maximum BFL (= 5300 ft).

The 44 seat design without power increase is only feasible if the wing aspect ratio is allowed to increase. All the designs with increased (scaled) thrust were feasible with wing aspect ratio fixed at 9.0. The optimum (min DOC) 48 seat configuration is seen to require an engine increase of about 22% with less wing than on the baseline aircraft. Using the same wing area as the original baseline

(40 seat) would require engine scales of +8% for the 44 seat version and 18% for the 48 seat aircraft. This 48 seat configuration is also shown to be the minimum first cost design at this size. Again the study showed the powerful effect of increased wing aspect ratio.

Objective function sensitivity

The optimisation method can accept any definition of the objective function. The sensitivity of the values for the optimum design parameters with respect to this choice is of interest. To this end, a series of optimisations was conducted on the baseline design with the same field specifications as used in the mission study:-

Design	Description
1	Baseline design, Object Function = Min.Wing Mass
2	As 1 with $LFL_{max} = BFL_{max}$ = 5300 ft
3	As 1 with Object.Function = Min. TO mass
4	As 3 with $LFL_{max} = BFL_{max}$ = 5300 ft
5	As 1 with Object Function = Min. Fuel mass
6	As 5 with $LFL_{max} = BFL_{max}$ = 5300 ft.
7	Baseline design, Object Function = Min.DOC/Flt.

The results are shown in figure D7 (appendix D).

The optimisation program is seen to be working correctly by the fact that in each case the objective function value is less than the values selected in other cases, for the restricted LFL specification the principal values are:-

	MWING	MTO	MFUEL	DOC	SMC	MCRUZ
Mass of Wing (MWING)	**3945**	37812	5581	2625	7.55	.62
Take-off Mass (MTO)	4060	**37548**	5251	2543	7.31	.62
Mass of Fuel (MFUEL)	4605	38036	**5107**	2503	7.19	.62
Direct Operating Costs(DOC)	4543	38425	5467	**2226**	**6.40**	.77

The relative values are shown below

	MWING	MTO	MFUEL	DOC
Mass of Wing (MWING)	**1.000**	1.007	1.093	1.179
Take-off Mass (MTO)	1.029	**1.000**	1.028	1.142
Mass of Fuel (MFUEL)	1.167	1.013	**1.000**	1.124
Direct Operating Costs(DOC)	1.152	1.023	1.070	**1.000**

It is clear that substantial (18%) savings are possible with the correct choice of objective function. This indicates the necessity to carefully consider the choice of objective function before the aircraft optimisation studies are started.

Relaxing the aspect ratio and LFL constraints shows a similar trend:-

	MWING	MTO	MFUEL	DOC	SMC	MCRUZ
Mass of Wing (MWING)	**3456**	36481	5260	2506	7.20	.63
Take-off Mass (MTO)	3552	**36214**	4943	2380	6.84	.65
Mass of Fuel (MFUEL)	4357	36885	**4683**	2443	7.02	.62
Direct Operating Costs(DOC)	4416	37708	5316	**2188**	**6.13**	.79

The relative values are

	MWING	MTO	MFUEL	DOC
Mass of Wing (MWING)	**1.000**	1.007	1.123	1.145
Take-off Mass (MTO)	1.028	**1.000**	1.056	1.088
Mass of Fuel (MFUEL)	1.261	1.019	**1.000**	1.117
Direct Operating Costs(DOC)	1.278	1.041	1.135	**1.000**

These show increased savings for the correct choice of objective function, reinforcing the earlier comment regarding the significance of aspect ratio selection in these designs.

The choice of objective function is seen to have the following effect on wing design:-

	ASPECT RATIO		WING AREA	
	AR free	AR <9	AR free	AR <9
Mass of Wing (MWING)	10.92	8.92	467.94	566.44
Take-off Mass (MTO)	10.65	8.72	464.71	562.55
Mass of Fuel (MFUEL)	13.00	9.00	470.78	568.78
Direct Operating Costs(DOC)	11.86	9.00	482.04	580.87

These results are reassuring since they indicate that within the feasible design region the wing area is not too sensitive to objective function choice. Again no allowance was made in the design equations for elastic stiffening which may affect the very high aspect ratio design selected above.

The effect on optimum flight profile (cruise Mach number) is clearly seen in the results above. For the minimum DOC cases a high cruise speed is selected to reduce block time whereas, for the minimum mass cases much lower speeds are chosen. In the reduced cruise speed cases the thrust setting in cruise is only about 70% of the value used for the DOC case. The increased block time adds

about 1 cent to aircraft seat mile cost for the 1000 mile stage, but the reduced aircraft mass cases lower aircraft price by about $0.3M.
It was felt that this study confirmed the selection of minimum DOC per flight as the correct choice of objective functions for all subsequent optimisation (except where stated).

Challenger studies

Shortly after the start of the fan-jet studies, Canadair announced their intention of developing their Challenger long-range jet executive aircraft into a commuter aircraft (Regional Jet). The engine used in this design is much more powerful than the CFE engine considered by Shorts for the FJX designs. To investigate the nature of this competition, two optimisations were conducted with the Challenger specification (48 seats and up-rated engine), the first (Design 1) with aspect ratio limited to 9.0 and the second (Design 2) with aspect ratio free. The results of these two studies together with previously optimised +20% CFE design (Design 3) are shown in figure D8 (appendix D).

Since the aircraft is considerably overpowered there is no advantage in freeing the upper limit to the wing aspect ratio. The optimum aircraft selects the minimum value of aspect ratio (7.5) to reduce wing mass. The WAT/BFL criteria are both shown to be uncritical. The LFL of 5300 ft dictates a wing area of about 620 sq.ft. The extra power available increases cruise speed to M0.81. The larger, thirstier engines increase aircraft TO mass by 5355 lb (15%) over the comparable CFE engined aircraft. The reduced block time of 487 seconds for the Challenger aircraft does not compensate for the influence of mass increase on the DOC prediction. This shows a substantial (11%) penalty for the Challenger. The most attractive advantage for overpowering the aircraft is the inherent potential for aircraft stretch. It was shown by two further optimisation studies that a growth to 68 seats would be possible with no engine change but with wing area increased to approximately 750 sq.ft. The results for aspect ratio limited to 9.0 and AR free are shown in appendix D (designs 4 & 5 on figure D8). Comparison of the baseline CFE aircraft (40 seats) with the Challenger (48 seats) on a seat mile cost basis shows no penalty for the larger aircraft. This demonstrates the powerful effect of seats (aircraft size) in SMC evaluation and prompted a review of the baseline design to increase the size to 44 or 48 seats. It was recognised that such a stretch would require more thrust from the CFE engine. The first cost of the RJ was quoted by Canadair to be about 50% more than the FJX baseline design. This cost penalty arises due to the increase in aircraft size (weight), the more expensive engines, and the commercial aspects arising from the existing Challenger Executive Aircraft price.

Summary

The first phase of the work demonstrated some of the different ways in which the optimiser/design model could be used in aircraft project design. The aircraft design studies provided information used in the preliminary design of the FJX layout. The following conclusions could be drawn:-

- The 40 seat baseline specification and the original CFE 738 engine are well matched but do not offer any immediate stretch potential unless the wing aspect ratio upper limit could be raised.

- The comparable multi-stage missions to the 1000 nm single-stage specification is not clearly shown, but the definition of the optimum aircraft configuration is not too sensitive to this choice. It was decided to conduct all subsequent optimisations on the single-stage format to allow comparision with industrial estimates.

- The rear-engine layout is less efficient than the corresponding wing-mounted configuration. The penalties for rear engine location on the baseline specification include an increase in DOC/flight of approximately 10%.

- Stretching the aircraft and retaining the current wing aspect ratio restriction would require 8% and 18% more thrust for the 44 and 48 seat designs respectively, to fly on the same wing as the baseline design. If the wing could be enlarged, less engine stretch would be required.

- The Challenger aircraft is seen to be substantially less efficient than either the baseline (40 seat) or the stretched (+20% CFE, 48 seat) design. The influence of aircraft size is shown by the fact that both the 40 seat baseline aircraft and the Challenger have similar seat mile costs. A 68 seat stretched version of the Challenger was shown to be possible with the existing engine thrust but would require substantial redesign to the fuselage, wing, tail and undercarriage structure.

5.1.2 FJX DEVELOPMENTS

In the nine months since the previous optimisation studies were completed, a lot of detailed design work had been conducted on the new FJX aircraft by Shorts[4]. Models, mock-ups and a full press release were presented at the Farnborough Air Show (1988) and a preliminary type record was prepared. Since the earlier studies, the thrust from the CFE engine had been increased slightly and this made it possible to stretch the original specification up to 44 passengers (or 48 with reduced range and more congested cabin layout). The full description of the FJX design is shown in figures 5.6 and 5.7.

Interest in the turbo-fan commuter market had expanded due to the firm commitment by Canadair to develop the Challenger RJ aircraft and the introduction into the market of a project design by Embraer (EMB-145). Airlines had expressed interest in larger aircraft sizes (50-80 seats) and were demanding a choice of engine installation from different manufacturers. Four contender engines had emerged at this time:-

(i) GE/Garrett CFE 738 (5700 lb TO thrust)
(ii) Pratt & Whitney PW300X (6473 lb TO thrust)
(iii) Texas/Lycom. ALF502R (7350 lb TO thrust)
(iv) Rolls Royce/Allison RB580 (6700 lb TO thrust)

All these engines are high bypass (≈ 5) designs. The CFE engine was still designated for the FJX aircraft but concern was raised at the relatively low level of thrust compared to the other engine options. It was decided to investigate the sensitivity of the FJX design to engine developments (thrust increases). It was agreed to consider aircraft stretches to 56 seats and 68 seats (3 and 6 extra rows of seats) with associated baggage and service space.

The optimisation model was modified to suit the latest FJX specification[5]:-

. fuselage capacity increased to 44 seats
. new CFE engine data
. stage reduced to 1000 statute miles
. balanced field length reduced to 5100 ft (in response to airfield availability and market study done at Shorts)
. WAT specification relaxed to +20°C ISA-SL
. Wing aspect ratio fixed at 9.27

Trial optimisation runs were made to assess the accuracy of the synthesis model compared to the FJX design and industrial performance calculations. This showed an underestimation of aircraft maximum weight. This was corrected by increasing passenger weight to 200 lb each. The trials also showed a slightly lower drag estimate and an underestimate of fuel usage. It was determined that the curve fitting routines used to model the new CFE engine data could account for about 5% of the fuel shortfall. The engine fuel flow data was therefore scaled to correct this effect. The wing lift coefficient was seen to be over estimated, so the basic wing section fixed input data was altered to reduce this discrepancy. After these changes had been included the optimiser was judged to be an acceptable simulation of the 44 seat FJX design even though the cruise fuel (or aircraft drag) was shown to be still underestimating by about 5% compared to equivalent calculations from Shorts. Since no technical justification could be made for further corrections to the synthesis model, this variability was accepted as 'designers discrepancy'.

The initial optimisations on the baseline design showed a wing area about 37 sq.ft smaller than currently used on the FJX design. Again this can be interpreted as a 'reserve' in wing size, held as insurance against weight growth or as potential for future stretch. The maximum aircraft weight is predicted lower than the FJX design which may be accounted for by the small wing area, lower stage fuel prediction and possibly the conservation of the industrial designers.

When the engine data is scaled in the program the parameter (ENGSC) is used to increase thrust, fuel flow, nacelle size, engine group mass, and engine cost.

A summary of each study in this section is shown in figure 5.8 and all the detailed results for each study can be found in appendix D (figures D9 - 16).

LFL Study

To identify the comparable optimum design specification to the FJX configuration, a series of optimisations were conducted with progressively reducing maximum landing field lengths. The results are shown in figure D9 (appendix D) and plotted in figure 5.9. The LFL = 4823 ft result provided the closest comparison with the actual FJX wing.

To check the choice of aspect ratio, a 'free' AR baseline design was optimised (Design 8). This suggested a value of 9.31. The resulting design showed only a small variability with the baseline configuration (with aspect ratio fixed at the slightly lower value of 9.27).

44 seat designs

The first series of optimisations was directed to the investigation of increased engine power on the non-stretched (44 PAX) aircraft. The results for engine scales of +5, +10, +15% are shown in appendix D (figures D10 Designs 3,4,5). Since all the aircraft are LFL critical, the increased power has the effect of making BFL/WAT uncritical and increasing cruise speed. As shown in figure 5.10 the wing area increases due to the heavier engine installation and greater fuel burn. The increase in aircraft first cost due to the more expensive engine and heavier aircraft is not offset by the lower flight cost which results from the reduced block time.

Apart from the improved single-engine climb performance, no case can be put foward for increasing engine size on the baseline aircraft. The extra engine power could be used to offset the drag increase which would arise from the introduction of double-slotted flaps (DSF). The increased maximum lift coefficient will reduce the required wing area to satisfy the LFL criteria. To investigate this effect, all the previous studies were re-optimised. The results are shown in figure D11 (appendix D). For the baseline design with the basic CFE engine, the improved flap relaxes the LFL requirement as expected, but the reduced L/D ratio in climb makes BFL/WAT more critical and therefore forces an increase in wing area. The new baseline design (Design 2) is seen to be less efficient than the old design with single-slotted flap (Design 1). The addition of 5% more thrust is sufficient to overcome the deterioration in L/D ratio and allows a 30 sq.ft reduction in wing area and about 250 lb reduction in aircraft TO mass. Combinations of improved flap and larger engines offer the best possibility for small stretches in aircraft size. Wing area and aircraft maximum TO mass variations are plotted for both types of flap and the engine scales, in figure 5.11. Although extra engine power is seen to only marginally affect wing area (≈+2%) it has significant influence on SMC (≈+20%). The inclusion of DSF significantly reduced wing area and flattens the area sensitivity to about +1% over the range considered. Seat mile cost is reduced by about 12% but the cost sensitivity curve is not otherwise affected. Only the +5% engine with DSF combination is shown to have better SMC than the baseline design.

The main advantage of extra engine power lies in the prospects for much larger increases in aircraft size. To investigate this effect two separate series of optimisations were conducted (56 seats and 68 seats). A layout study showed that the fuselage length (LF2) for each of these stretches should be 15.65m and 19.76m respectively. These sizes were based on a seat pitch of 34 inches, extra baggage space, and extra toilet/galley services (68 size only).

An analysis of market information conducted by Legg[2] suggested stage/field length combinations for larger aircraft:-

68 PAX : 1040 nm stage , 6200 ft field
56 PAX : 1010 nm stage , 5700 ft field
(c.f. 44 PAX : 960 nm stage , 5100 ft field)

56 seat design

The results for all the 56 seat optimisations are shown in figure D12(appendix D). The study pattern is shown below:-

Design	Engine Scale	
1	1.0	Single-slotted flaps
2	1.1	Single-slotted flaps
3	1.2	Single-slotted flaps
4	1.3	Single-slotted flaps
5	1.0	Double-slotted flaps
6	1.1	Double-slotted flaps
7	1.2	Double-slotted flaps
8	1.3	Double-slotted flaps

As expected for this size of aircraft, the unscaled CFE engine with both types of flap is shown to be unfeasible. Even with a +30% engine the design requires a larger wing than the current FJX (44 seat) design. Only by the introduction of DSF can the design be brought down to about the existing wing size. An engine scale slightly less than +20% coupled with single-slotted flaps and a small wing tip extension would provide the best compromise for the 56 seat size.

68 seat design

The 68 seat optimised aircraft are shown in figure D13 (appendix D).
The study pattern is shown below:-

Design	**Engine Scale**	
*1	1.2	Single-slotted flap
2	1.3	
3	1.4	
4	1.5	
*5	1.2	Double-slotted flap
*6	1.3	
7	1.4	
8	1.5	

* These designs did not converge onto a feasible design.

Only the + 40% and +50% engine scales lead to acceptable designs. Again the effect of incorporating DSF is seen to be only of value to the +50% design. This study showed that the 68 seat aircraft is feasible on the current FJX wing with DSF (in effect requiring a third engine). The substantial increase in TO and landing speeds compared to the baseline (44 seat) design confirms the layout to be considerably 'underwinged'. With a modest increase in wing area (75 sq.ft) a feasible design could be produced with a +40% engine scale (i.e. the 10000 lb take-off thrust engine).

At this point in the study preliminary details of the new Rolls Royce engine (RB580) became available. It was decided to remodel the engine data to suit this engine thrust and conduct a new series of optimisation. The CFE engine data was crudely scaled to the new RR data and a series of ten aircraft were designed for direct comparision with the CFE studies above.

44 seat new designs

The first three optimisations with the new engine were associated with the original 44 seat/CFE engine specification. The results together with comparable designs from previous work are shown in figure D14 (appendix D).

The study pattern is shown below:-

Design	Engine	Flap	Notes
1	1.0 CFE	SSF	Max LFL = BFL
2	1.0 CFE	SSF	Max LFL = 4822
3	1.0 CFE	DSF	Max LFL = BFL
4	1.15 CFE	SSF	Max LFL = BFL
5	1.15 CFE	DSF	Max LFL = BFL
6	1.0 RR	SSF	Max LFL = BFL
7	1.0 RR	SSF	Max LFL = 4822
8	1.0 RR	DSF	Max LFL = BFL

The first RR aircraft (Design 6) is a re-engined version of the baseline design (Design 1). The results show that the extra power from the RR engine makes BFL/WAT uncritical. The LFL remains dominant and forces an increase in wing area to compensate for increased engine and fuel weight. The specified wing area for this case is close to the actual FJX design, thereby suggesting that a straight re-engining would be possible (confirming the strategy of the FJX project designers in reserving some wing area in the initial design!). The extra cruise thrust increases speed to the maximum M0.85 allowed in the program (i.e. assuming the wing aerodynamic design can be arranged to effectively avoid significant compressibility drag at the wing sweep specified). This increased speed substantially reduces stage time which reduces DOC to completely erode the increased DOC cost effect due to the higher aircraft price. This result makes the RR engine baseline design a strong contender in subsequent project work.

The second study (Design 7) tightened LFL to that used earlier to allow direct comparison with the actual FJX aircraft. This strategy is not recommended in this case as the LFL forces an increase of 50 sq.ft to the wing area (above the FJX size). The extra power again raises the prospect of using DSF. The third study (Design 8) shows that the introduction of double slotted flaps has the effect of restoring some of the original 'reserve' wing area into the baseline design. The reduced L/D ratio in climb resulting from the double slotted flaps shows the expected increase in BFL. The increase is not sufficient to make BFL critical. WAT is also shown to be uncritical in this design. The increased maximum lift coefficient allows a reduction of about 40 sq.ft in the wing area making the size similar to the earlier 44 seat (CFE powered) design. The reduced aircraft mass resulting from the smaller wing, improves all the cost parameters and produces the best 44 seat aircraft found on a DOC per flight (or seat mile cost) basis. The aircraft price, however, is higher than the baseline CFE aircraft.

56 seat new design

Three studies were completed on the 56 seat stretched version of the aircraft. The results are shown in figure D15 (appendix D) together with comparable designs from the previous CFE study.

The study pattern is shown below:-

Design	Engine	Flap
1	1.2 CFE	SSF
2	1.3 CFE	SSF
3	1.2 CFE	DSF
4	1.3 CFE	DSF
5	1.0 RR	SSF
6	1.1 RR	SSF
7	1.2 RR	SSF

The first study (Design 5) represents a straightforward re-engining of the previously unfeasible CFE powered design. In this case the extra power from the RR engine makes the design feasible but it requires a wing area about 100 sq.ft greater than the FJX design. Since WAT/BFL is seen to be critical it is impossible (without extra power) to reduce this area by the inclusion of DSF.

To investigate the influence of extra power (i.e. RR engine stretch), two further studies (Designs 6,7) were conducted at +10% and +20% engine growth. The first 10% is sufficient to make the design WAT/BFL uncritical. Extra growth beyond has no advantage. Extrapolating between the non-stretched and +10% designs shows that a 56-seat design would be well matched with a RR engine of about +5% growth. This design would require a slight increase in the current FJX wing area. A separate configuration study showed that a tip extension of 18 inches and a flap chord increase of 6 inches would match the extra wing area rquired for this design. Such an aircraft would be the 'best DOC' design found in the studies for 56 seat aircraft.

68 seat new designs

To be feasible, this size of the aircraft would obviously require RR engine stretch. To determine the relationship between engine and aircraft stretch, four optimisations were performed (i.e. +20%, +30%, +40%, +50%). The results are shown in appendix D (figure D16 Designs 5-8) together with comparable CFE designs from the previous study with 1.4, 1.5 CFE engines, with SSF and DSF (figure D16 Designs 1-4).

All four RR studies showed f easible designs but an unusual pattern of results was obtained. The +20% design followed the usual pattern, with WAT/BFL critical and LFL not critical. This shows the aircraft to be slightly underpowered as the single-engine climb gradients could only be achieved by increasing wing area above that required to meet the landing criterion (i.e. an attempt to improve climb by reducing span loading). The aircraft requires a wing area about 80 sq.ft larger than the current FJX aircraft.

The next study (Design 6 with +30% extra thrust) produced an unusual result. Repeated re-optimisations with different sets of variable starting values still converged on the same design. This strange choice is seen clearly in the selection of cruise height at 18000 ft. (All other designs select 36000 ft). This reduced height obviously saves in climb time and yet the aircraft is seen to have sufficient power to provide M.85 cruise speed. The savings in block time of 9 minutes improves aircraft DOC even though about 900 lb more fuel is consumed. The aircraft is well 'balanced' with BFL and LFL equally critical. This 'rogue' result must be examined closely as it suggests the aircraft is better suited to short-haul stages than might have been expected. It also offers the prospect of more flexibility to air traffic control demands.

It would be easier to explain this result if the next two studies (Designs 7 & 8, with +40 or +50% engine stretch) followed the same pattern. As can be seen in figure D/6 these designs returned to the same pattern as all other designs and selected 32800 ft. for cruise height. One can only assume that the extra thrust in these designs allowed a quicker climb segment and this proved to be more economic to the optimiser.

Note, all the four studies showed improvements in aircraft operating cost figures compared with the previous CFE designs. They gave the best DOC/flight design but with increased aircraft price.

Summary

The Rolls-Royce engined aircraft appear to offer the best choice for aircraft stretch. Although the 44-seat designs are overpowered by the basic engine, the increased cruise speed available makes it an attractive choice. With only a modest (+5%) increase in power from the basic engine, a stretch to 56-seat seems feasible without changes to the existing (Shorts FJX)wing. The stretch to 68-seats would require a substantial (+25%) basic engine stretch but this compares to the three-engine design requirement (i.e. +50%) necessary from the CFE powered designs. The wing area for the 68-seat design would need to be increased by about 40 sq.ft. to match the +25% engine stretch or by 80 sq.ft for a +20% stretch.

The inclusion of double-slotted Fowler flaps in the design would only be an advantage for those aircraft with excess available power. Changing to these flaps for power-limited designs is a disadvantage. When extra engine power is available a subtle trade-off exists between increased power plus DSF and reduced aircraft wing area. The powerful effect of speed (block time) on DOC is shown by the RR engine studies. This indicates that extra power is economically attractive if it can be translated into increased cruise speed, and may suggest that the choice of more powerful engine is desirable on a DOC basis but a disadvantage with respect to aircraft purchase price .

5.1.3 FJX/RR STRETCH STUDIES

The second phase of industrial design studies had identified the competitive position of the Rolls Royce RB580 - engined aircraft, particularly with regard to the stretched versions of the basic design. This third phase of studies was intended to more accurately simulate the new RR engine and to show the implications for the choice of stage and field length specification of the stretched aircraft. Due to the preliminary nature of the design data for the RR engine, the previous phase had only crudely matched RR data to CFE performance at a single take-off thrust scaling. For this third phase detailed engine performance data was obtained from the manufacturers but, due to difficulties arising from the discontinuous nature of the curves, it was found to be impossible to accurately curve-fit the data to suit the optimiser. Tri-linear interpolation of the data was attempted but found to be too slow for the frequent calls to the engine data made by the synthesis program. Due to these problems it was decided to model the RR engine using scaled output from the CFE data. Different values for the scaling factors were evaluated for the take-off, climb and cruise phases for thrust and fuel flow (see section 4.4.7). Trial calculations showed this simulation to predict the data with acceptable levels of accuracy (±2%) in the critical operating regions.

In this third phase of the work, three separate study areas were investigated:-

(i) the *current* RB580 engine performance

(ii) the *near-term* (within 2 years of certification) at which the engine thrust will be raised by +8% throughout all operating conditions.

(iii) the *far-term* (i.e. the maximum development potential for the basic engine configuration) at which the thrust would be raised by 40.8% from the current standard.

From the details provided by the previous work, the first two study areas were limited to the 56 seat version of the current FJX aircraft configurations. Various stage and field length specification were investigated as shown in figure 5.12.

The first study (engine Scale = 1.00) considered four stage distances (700, 900, 1100, 1300 sm) and three field lengths (5700, 5900, 6100 ft) in combination. A total of 12 optimisations. The second study (engine scale = 1.08) considered the same stage distances as the previous study in combination with four field lengths (5300, 5500, 5700, 5900 ft). A total of 16 optimisations. The third study area considered four different aircraft sizes (68, 72, 76, 80 seats) at several stages (1100, 1300, 1500, 1700 sm) and two field specifications (6100, 6300 ft). A total of 32 optimised designs.

Since the completion of the previous design studies, it had been determined that airlines required more flexibility in operational weight. To this end, the program was modified to add a 5% contingency to OEM for all subsequent studies.
To validate the new program, the previously specified 44 seat baseline design was altered to run on the RR data with 48 seats. Stage length (1100 sm) and field length (5100 ft) were set as representative of the current FJX specification. The results showed an aircraft that was substantially over-powered with wing area, maximum TO mass and LFL similar to the current FJX design. The program was regarded as predicting this size of aircraft with sufficient accuracy.

Current engine

The results of optimisation from the first study are shown in appendix D (figure D17). All the aircraft are shown to be feasible except the heaviest (longest stage/shortest field) Design 4 which did not converge onto a sensible configuration. This suggests an upper limit of about 52000 lb (MTOW) for the current RR engine. The results are carpet plotted against wing area (figure 5.13) and MTO (figure 5.14). With the simple wing tip and trailing edge extensions mentioned earlier, the current FJX wing area could be extended to 625 sq.ft. Extrapolating across figure 5.13 provides the stage/field length combinations to match this new wing. These are plotted in figure 5.15 together with ± 5% sensitivity lines.

Figure 5.13 and 5.14 show the aircraft to be more sensitive to changes in field length than stage distance. A 10% change in field length requires 100 sq.ft wing area increase, whereas a 10% stage alteration affects the area by only 25 sq.ft. Alternatively, from figure 5.15 these sensitivities can be considered in terms of a 10% change in wing area providing 20% (200 sm) change in stage distance or a 7% (400 ft) change in field length. These results confirm the desirability of specifying field performance as wide as the market will allow.

Near -term engine

The near-term engine studies are shown in appendix D (figure D18). The extra power available overcomes the problem identified for the heavy aircraft of the earlier 56 seat designs. No upper limit on aircraft weight was identified by the optimum aircraft design points considered. This suggested the potential for aircraft stretch to 60 or 64 seats.

As a postscript to this part of the study, four extra design points were investigated to determine the extent of further stretch potential. Aircraft with 60 and 64 seats, flying 1100 and 1300 sm stages with a field requirement of 5500 feet were analysed. The following results were obtained:-

Spec	Area	MTOW	BFL	LFL	WAT
60/1100	732.67	535650	5500	4718	.024
60/1300	842.78	568379	5500	4324	.024
64/1100	Failed: BFL/WAT criteria violated.				
64/1300	Failed: BFL/WAT criteria violated.				

An upper limit of 60 seats is feasible with the near-term engine but this design does require substantial wing area increase above the current FJX wing design.

The 56 seat aircraft designed for the shorter stages are seen to be overpowered (BFL and WAT uncritical). This leads to a change in the active design constraint from take-off/climb to landing. This effect is clearly shown in figure 5.16. The 700 and 900 stage results are seen to be weight penalised. To a lesser extent, a similar influence can be seen in the wing area graph (figure 5.17).
To assess the extent of the overpowering effect, four extra studies (700, 900, 1100, 1300 stages) were undertaken for aircraft with a reduced field specification (5100 ft.).

All the extra studies produced feasible designs as shown below:-

Stage	Area	MTOW	BFL	LFL	WAT
700	607.35	48180	5017	*5155*	.024
900	628.15	49116	5100	5034	.024
1100	684.09	50786	5100	4764	.024
1300	773.09	53241	5100	4419	.024

The shortest stage aircraft slightly violates the landing field constraint. This may be due to relaxed optimiser tolerances which are unduly influenced by the overpowered designs. The above results are plotted on the area and weight graphs (figures 5.16 and 5.17). At the reduced field requirements, the overpowering effects seen in the earlier studies are shown to be avoided. Comparison of the current and near-term results for the 1100/1300 stages at 5700/5900 fields show the trade-off on aircraft wing area for the 8% engine thrust increase (figure 5.13). A reduction of 150 sq.ft. wing area and 1200 lb MTO weight is available. These may be regarded as extremely beneficial cost-effective trades, since the cost of engine development would be substantially less than the corresponding aircraft price and operating cost increases.

The near-term engine combined with the slightly extended FJX wing was investigated by extrapolating from the results plotted in figure 5.17. The resulting trade-off between stage distance and field length is shown in figure 5.18 together with ±5% sensitivity lines.

Far-term engine

The results from all the far-term optimisation studies are shown in appendix D (figure D19) and the values for wing area and aircraft MTOW are carpet plotted in figures 5.19 to 5.22 for both field specifications.

As the aircraft size and stage increased towards the top of the range, the available power is unable to satisfy the WAT/BFL requirements. In such cases the optimiser is unable to find a feasible design point. This affected the 76 seat aircraft at maximum stage and all the 80 seat aircraft except the shortest stage distance. All these designs exceed 65300 lb MTOW which seems to suggest this limit for the far-term engine stretch.

As the power available approaches the critical region mentioned above the optimiser chooses to fly the aircraft slower to reduce fuel mass and thereby MTOW. Typically, the cruise speed reduced from M.8 to M.7. This achieves a feasible design but at a higher operating cost. This influence was seen on the short stage 80 seat/1100 and the 76 seat/1500 stage aircraft. Although technically feasible, these designs are not regarded as satisfactory from an overall viewpoint.

For the aircraft specifications which were overpowered the optimiser switches the critical constraint from WAT/BFL to LFL (i.e. similar to some of the near-term results). This occurred at aircraft maximum take-off weights below 61000 lb and affected the 68/1100 68/1300 and 72/1100 designs. Overpowering is shown to provide no advantage to the aircraft.

As only two field lengths were investigated (6100 and 6300 ft) it was not possible to identify if the larger aircraft (e.g. 80 seat) specification could have been made feasible with a substantial relaxation in this constraint. It was possible to note that 200 ft relaxation in field length translated into a wing area reduction of about 25 sq.ft and an MTOW reduction of 400 lb.

The differing influences exerted on the design by both under- and over-powering showed the far-term engine to be well matched to 72 seat design at the stages and field considered.

Aspect ratio sensitivity

In early trials, the influence exerted by the choice of wing aspect ratio was shown to be strong. To further demonstrate this effect 12 extra design points. with fixed aspect ratios in the range 8.8 to 11.0 were optimised with the new model. The results (appendix D figure D20) show a progressive variation of area and MTOW for the fixed aircraft specification (56 seats, 900 stage, 5700 field). Over the full range of aspect ratio considered and plotted in figure 5.23 the wing area reduced by 90 sq.ft., the weight reduced by 700 lb and the block time shortened by 300 seconds. The larger wing areas had the effect of reducing LFL by 500 ft. over the values for the smaller wings. These are substantial effects which provide good prospects for future aircraft development.

Summary

The optimisation studies identified the suitability of the Rolls Royce engine for particular aircraft stretches:-

- The current engine is well suited to the 56 seat stretched baseline aircraft.
- The near-term engine development is seen to overpower the short range 56 seat designs but is suitable for the larger (+ 1100 stage) designs. This engine could allow a reduction in field length to about 5000 ft for the 56 seat aircraft.
- The near-term engine could power a 60 seat design if stage was restricted to a maximum of 1300 sm. It is not powerful enough to suit 64 seat design.
- The trade-off between engine thrust increase and aircraft parameters (area and weight) is seen to be substantially in favour of engine changes.
- The far-term engine development is well matched to the expected 72 seat stretch but would be unsuitable for 80 seat designs.
- The influence of wing aspect ratio choice is seen to be powerful. All the power-critical designs in the study would have benefited from a relaxation in the fixed 9.27 value used.

5.1.4 PERI-OPT STUDY

To allow the designer to identify the flexibility in choice of design values, the sensitivity of the optimum design to changes in the main variables is required. The PERI-OPT option provides this information. The study which resulted in the closest match to the current FJX design was analysed by this facility to show the main wing geometry sensitivities (wing area and aspect ratio). In this version of the program a ±15% variation about the optimum values was displayed. Only the centre point on each of the diagrams represented a 'true' optimum configuration (for minimum DOC per flight) but within the accuracy of the estimating models the design surfaces will be close to the true optimum design surface.

The results of this investigation are shown in the following figures:-
5.24 to 5.27 show the mass surfaces (MWING, MFUEL, M(WING + FUEL), MEMPTY)
5.28 to 5.30 show the field requirements (WAT gradient, BFL, LFL)
5.31 & 5.32 show the cost surfaces (DOC per flight, SMC)
5.33 shows the combined constraints and variable curves through the optimum point.

The most notable feature of all these diagrams is the relative smoothness of the surfaces. For the mass surfaces the greatest sensitivity is seen on the wing mass (as might have been expected since wing geometry was under investigation) with a substantial 50% variation over the ±15% geometry range investigated. In comparison, fuel usage is seen to be relatively insensitive with only a 7% variation. The total effect on aircraft empty weight is seen to be about 7%. For the field criteria, WAT is seen to be about twice as sensitive as the other two parameters. LFL is seen to be slightly more sensitive than BFL and variable by about 20% over the full range. The direction of the slope of the BFL and LFL surfaces is seen to be approximately the same whereas the WAT (a gradient calculation) is shown to be orientated at about 90° to these constraints. This obviously directs the optimum designs into the intersection of the WAT and BFL (or LFL) constraint boundaries. The cost surfaces show about 7% variation over the geometry range with a surface direction approximately in line with the BFL/LFL surfaces. This makes cost relatively insensitive to aspect ratio variation. The choice of optimum design is clearly demonstrated in figure 5.33 in which the top right quadrant represents the only feasible design region. These graphs clearly demonstrate the design choice and the influence of wing geometry on the main parameters.

5.2 Generalised Design Studies

The industrial related studies of section 5.1, were associated with particular engine and aircraft configurations. Some combinations were shown to be unfeasible. The project design methods developed in the earlier work had been modified to allow engine and aircraft to be optimised together in a generalised manner. In this way, the best combination of engine and airframe can be determined for a particular operational specification. By schematic application of this method, it is possible to describe aircraft design surfaces. These 'generalised' surfaces can be compared with current and projected specifications of engines and aircraft to provide guidance on design strategy. To illustrate this method, four study areas are described:-

(a) Generalised designs
(b) Mass estimation sensitivity
(c) 80 seat designs
(d) Wing aspect ratio sensitivity.

The optimisation method in these studies incorporates 'engine scale' as a design variable. This allows the optimum engine size to be matched to an aircraft configuration for a particular mission (seats, stage, field). The study patterns are shown in figures 5.34, 5.40 and 5.42.

For comparison with the earlier study results the RB 580 engine data was used as the baseline powerplant and the fixed input data, as validated against the FJX aircraft, used for the aircraft baseline. Although most of the studies conducted in this series are concerned with larger aircraft and engines than the baseline specifications, it was accepted that the scaling effects were accurately modelled in the synthesis program.

5.2.1 GENERALISED DESIGNS

A 27 point 'carpet' study of seats (60, 72, 80), stage distance (1000, 1250, 1500 nm) and field length (5800, 6100, 6400 ft) was conducted. The results are shown in appendix D (figure D21 (60 seats), D22 (72 seats) and figure D23 (80 seats). The specification for each size of aircraft is similar in each table:-

Design	Stage(nm)	Field (ft)
1	1000	5800
2	1000	6100
3	1000	6400
4	1250	5800
5	1250	6100
6	1250	6400
7	1500	5800
8	1500	6100
9	1500	6400

Values of the principal design parameters are plotted in figures 5.35 to 5.39. These diagrams are drawn to permit interpolation for number of seats (more precisely seat rows). In each case, fuselage length is varied by 1 metre per seat row (4 abreast). Seat pitch is assumed to be 34 inches and the extra 6 inches is included for extra baggage and cabin service area space.

The objective function for all these studies is minimum DOC per flight. The optimiser selected aircraft which cruised at maximum permissible Mach number (0.80). This result confirmed the powerful effect of cruise speed on operating cost for this type of aircraft.

Since increased engine power is identified by the optimiser to be more economic than increased aircraft size (wing area, flap size etc), the overall design strategy becomes straightforward and matches traditional (non-computer) methods. The program selects a wing area to meet the landing field requirement and then selects an engine scale and take-off flap setting in combination to satisfy the WAT/BFL specification. Take-off flap settings are slightly larger than would be expected, but this may be due to inaccuracy in flap modelling. The design strategy forces engine scale to be relatively insensitive and wing area to be highly dependent on field length specification. Since engine size increase is regarded as cheaper than wing structure changes it may be economical to use more sophisticated flaps. This aspect has not been investigated because a satisfactory function to simulate flap mass and cost estimation could not be determined. This type of investigation could form the basis for an extension to the current work. The carpet plots confirm the underpowering effects highlighted in the industrial related studies. Previously, even the 76 seat designs were shown to be unfeasible with the engine development projected by the manufacturers. Only by increasing the optimum wing area would it be possible to produce feasible designs with such engine size limitations.

Over the range of stages considered (1000 to 1500 nm), the required engine improvement (for a particular aircraft size) is seen to be approximately /.12 scale. The same engine increase is shown to be required for changes between aircraft size (60 to 70 seats) for a given stage specification. This equates to about 8% thrust increase which may be regarded as within the near-term (less than 5 years) development period.

In association with the engine stretch discussed above, a wing area increase of approximately 15% would be necessary. This may present more difficulty than the engine development. This concern may therefore support the overwinging of the original configuration as a prudent design strategy. As the aircraft size increases, the change in engine scale requirement reduces and the wing area increase drops to about 8%. It may be possible to achieve this area increase with wing tip and wing chord extensions from an existing design. Part of the reduction in area increase is due to the law of diminishing return (a 12 seat extension on the 60 seat design represents an increase of 20% whereas 12 seats on a 72 seat design is only a 16.7% increase).

The engine scale requirements show an insensitivity to field length specification. This is shown clearly in the aircraft mass plots (empty and MTO). Stage distance is considered over a much wider range of values (50% increase) and this produces a 6% aircraft weight change.

The seat mile cost carpet plot (figure 5.39) shows the powerful influence of PAX and the relative insensitivity of stage distance beyond 1250 nm. Again the influence of diminishing returns can be observed between the 60 to 72 and the 72 to 80 aircraft stretches.

Many design strategies can be argued from these results, especially for the cases in which the engine and aircraft sizes are unconstrained. This situation does not often occur in industrial design projects as limitations on size and cost aspects will dominate. The cost analysis has shown the advantage of increasing size up to about 68 seats with a stage at 1250 nm and a field length set as long as the market allows. The sensitivity of the design surface to wing size translates into a confirmation of the designer's natural instinct to slightly overwing the initial configuration.

The range of aircraft considered in this study would require an engine with development potential to about 12000 lb take-off thrust. This would relate to a current engine of about 8500 lb. None of the engines considered in the industrially related studies were as powerful as this.

5.2.2 MASS ESTIMATION SENSITIVITY

In aircraft project design there is always an uncertainty regarding the accuracy of mass predictions for the aircraft components. Also, with changing technologies, the introduction of new materials and manufacturing methods offer the prospect of mass reductions.

For both these reasons (at least) the designers need to know the trade-offs on aircraft parameters for mass changes. To this end, a series of design studies have been performed with mass predicted lower than in the previous studies. The aircraft operational empty mass was arbitrarily reduced by 5% (i.e. removing the contingency allowance introduced in response to airline requirements in the earlier industrially related studies). The mid-size aircraft (72 seats) was selected as representative of the range. The optimisation results are shown in appendix D (figure D24) and the effect on wing area is plotted in figure 5.41.

The following observations may be drawn from the results:-

1. The 5% OEW reduction returns a 4.3% saving in engine scale, viz:-

Stage (nm)	1000	1250	1500
	Engine Scale		
100% OEW Design	1.431	1.498	1.563
95% OEW Design	1.369	1.433	1.497

2. By coincidence the choice of stage distance intervals in the above table shows the trade-off between engine scale and stage. The 5% weight reduction returns a 250nm stage improvement (20%) for the same engine specification.

3. As in the earlier studies the engine scale is shown to be insensitive to field specification, therefore a trade-off in this variable is not viable.

4. Similar results to those in the table above are shown for the weight trade-offs, viz:-

Stage (nm)	1000	1250	1500
	OEW		
100% OEW Design	36724	37600	38398
95% OEW Design	35877	36742	37567

Stage (nm)	1000	1250	1500
	Max TO Weight (lb)		
100% OEW Design	62484	64731	66883
95% OEW Design	59837	61644	63747

- again a 250 nm increase in stage length is predicted for the lower weight designs. The 5% OEW reduction translates into slightly less than 5% reduction in MTOW and a 2.3% reduction in empty weight.

5. The wing area plot (fig. 5.41) shows a significant 30 sq.ft reduction for the reduced weight designs. For a given wing area the graphs show a 250 ft field length reduction for a given stage length, or by extrapolation a 900 nm stage

increase for a given field specification. Although these benefits may not be fully realisable they show the substantial advantages available and confirm the traditional designers view that for aircraft with a large zero-fuel weight ratio, the influence of weight saving is crucial. A simple analysis of the results shows that the 5% OEW saving equates to approximately 25% of the stage fuel (ignoring climb and descent variation and the effect of weight growth).

The mass sensitivity study confirmed the advantages associated with the introduction of advanced-technology materials and construction, for this type of aircraft.

5.2.3 80-SEAT DESIGNS

This study is used as an example of the generalised design method applied to a particular aircraft specification. The 80 seat size was selected because the earlier (industrial) studies had resulted in unfeasible design when limited by the far-term engine development. It was of interest to know by how much the previous engine size was underpowered. The same aircraft database was used as the earlier work. A twenty-point design surface was explored, viz:-

Stage (sm)	900,	1100,	1300,	1500,	1700
Field (ft)	5900m	6100,	6300,	6500	

- all the optimisations were successful. The results are shown in appendix D (figure D25) and carpet plots of the principal aircraft parameters are drawn in figures 5.43 to 5.48. The results form a consistent set and indicate trends that were expected (confirming the praticability of the synthesis model).

Figure 5.43 shows the optimum engine scales (RB580) to fall within the range 1.49 to 1.69 and thereby confirm the earlier study results (unfeasible at 1.408 scale). The engine scale is seen to be approximately linear with stage distance within the range considered. The engine scale is seen to be insensitive to field length requirement, particularly at the longest stage specifications. This result may be explained as earlier.

Figure 5.44 shows the wing area for optimum design to be sensitive to both stage and field specification. In the mid-range a 200 ft field length reduction equates to a 600 sm stage reduction for a constant wing design. Hence, field length is seen to be extremely sensitive to wing area specification. Over the range of specification considered, the required wing area varies between 630 and 740 sq.ft. (a 17% area growth). These results suggest that both field and stage lengths must be carefully selected. Also, provision must be made in the initial design for simple wing area growth (tip and chord extensions) if minimum wing size is initially selected.

Figure 5.45 again shows stage and field to be sensitive parameters in empty weight prediction. In this case a 200 ft field reduction corresponds to only about 800 sm stage reduction for a constant empty mass. Over the range of values considered, the aircraft empty weight increaes by about 8%. The MTOW variation shown in figure 5.46 changes by 11% over the full set of values. MTOW is seen to be more sensitive (≈ 500 sm) to stage changes than field reduction (200 ft).

Figures 5.47 & 5.48 show the effects on cost prediction. As expected with a wide variation in stage distance, the cost per flight nearly doubles ($2900 to $5500). The results show a high sensitivity to stage distance and relatively low sensitivity to field length. Both parameters appear to be approximately linear functions with DOC. This linearity disguises the absolute cost effect. This is shown more clearly in the seat mile cost graphs (Figure 5.48). These curves show the effect of diminishing returns for increasing stage length. A value of 1300 sm appears to offer the best choice for the 80 seat configuration. The seat mile cost is shown to be approximately linear with field changes. Unlike the earlier plots, field length is shown to be more sensitive than stage, when considering seat mile costs, particularly for stages above 1300 sm. This change in field sensitivity is interesting since pre-optimisation studies would have been based on wing and engine weight. For weight criteria the field length is seen to be less sensitive.

5.2.4 WING ASPECT RATIO SENSITIVITY

To allow comparison between the generalised studies and the earlier work, the wing aspect ratio was fixed at 9.30. (i.e. close to the previously optimum value of 9.31 and slightly higher than the 9.27 used in the earlier work). It was not known if the sensitivity of the design to aspect ratio change was affected by the increase in aircraft size. To show the influence of aspect ratio on aircraft parameters a series of generalised design studies was performed around the 'baseline' 72 seat aircraft. The aspect ratio range was restricted to values consistent with wing-stiffness provision (i.e. 9.7, 10.2, 10.7). The results are shown in appendix D (figure D26) and the effect on the principal aircraft parameters is plotted in figures 5.49 to 5.53.

As anticipated, all the results show a substantial advantage to the selection of higher aspect ratio than the 9.30 used in the previous work. Although improvements in empty weight and wing area are shown to be reducing at the higher values, all the other parameters (MTO, engine scale, DOC) are shown to be strongly active throughout the range. Engine scale is seen to be the most sensitive parameter and this matches the conclusion reached in the earlier studies, that engine size is shown to be extremely sensitive to wing geometry.

This study confirmed the recommendation from earlier work: that wing aspect ratio should be increased to the maximum value possible (taking into account wing stiffness criteria).

5.2.5 SUMMARY

The four study areas of section 5.2 each provided specific recommendations for the design of aircraft in the range considered. The weight reduction and the aspect ratio study indicated the desirability for adoption of advanced technology improvements. The use of double slotted flaps may be an advantage if engine power is not limited. The main recommendations centre on the preference for engine stretch in place of aircraft (wing) stretch to satisfy specific aircraft developments (size, stage or field increase). In practice, engine developments will be limited and a combination of engine and wing stretch will be necessary.

References for chapter 5

1. Jenkinson, L.R., Maccabee, F.G., and Simos, D.
   'Aircraft Design Optimisation Studies'
   Contractor's report for Short Brothers Plc. (Dec.1986 & Feb. 1987)

2. Legg, K.C.L.
   'Operator requirements for turbo-fan commuter aircraft..'
   Contractor's report for Short Brothers Plc. (April 1988)

3. Short Brothers Plc.
   'New aircraft project-configurational studies'
   Internal company report (October 1986)

4. Flight International
   'Shorts plans to put jet among the props'
   (19 March 1988, p4.)

5. Short Brothers Plc.
   'FJX Project - Type Specification (Preliminary)'
   Internal company report FJX/TS (issue 2), (Sept 1988).

Baseline Study (40 seats), (ref. figure D1)

1.	Baseline design with BFL = LFL = 5300 ft
2.	As 1 with LFL reduced to 4660 ft.
3.	Shorts initial design with BFL = 5270
4.	As 2 with emergency boost introduced to engine

Wing Geometry Study (40 seats), (ref. figures D2 and D3 respectively)

1.	As baseline 2 above with	Taper Ratio = .24, Thickness	= .15
2.	"	Taper Ratio = .30, Thickness	= .15
3.	"	Taper Ratio = .35, Thickness	= .15
4.	"	Taper Ratio = .24, Thickness	= .13
5.	"	Taper Ratio = .24, Thickness	= .11

1.	As baseline 2 with	Aspect Ratio	=	9.0
2.	"	Aspect Ratio	=	10.5
3.	"	Aspect Ratio	=	10.0
4.	"	Aspect Ratio	=	9.5
5.	"	Aspect Ratio	=	8.5
6.	"	Aspect Ratio	=	8.0
7.	"	Aspect Ratio	=	7.5

Mission Study (40 seats) , (ref. Fig.D4)

					Mission nm
1.	As baseline 2 above with	Aspect Ratio	= 9.0,	and	1 x 1000
2.	"	Aspect Ratio	= Free,	and	1 x 1000
3.	"	Aspect Ratio	= 9.0,	and	34 x 200
4.		Aspect Ratio	= Free,	and	4 x 200
5.	"	Aspect Ratio	= 9.0,	and	3 x 250
6.	"	Aspect Ratio	= Free,	and	3 x 250
7.	"	Aspect Ratio	= 9.0,	and	2 x 400
8.	"	Aspect Ratio	= Free,	and	2 x 400

Engine Position Study (40 seats), (ref. figure D5)

1.	As baseline 1 above (wing mounted engine)
2.	As baseline 2 above (wing mounted engine)
3.	As baseline 1 above (with rear fuselage engines)
4.	As baseline 2 above (with rear fuselage engines)

Figure 5.1 (sheet 1) Initial Studies

Stretch Study (BFL = 5300, LFL = 4660, AR = 9.0 , (ref. Figure D6)

*1** Seats = 44 and Engine Scale = 1.00
2. Seats = 44 and Engine Scale = 1.00
3. Seats = 44 and Engine Scale = 1.10
4. Seats = 44 and Engine Scale = 1.15
5. Seats = 48 and Engine Scale = 1.10
6. Seats = 48 and Engine Scale = 1.15
7. Seats = 48 and Engine Scale = 1.20
8. Seats = 48 and Engine Scale = 1.25
(*unfeasible design specification)

Objective Function (OJF) Study (40 seats) , (ref Figure D7)

1. As baseline 2 with OJF = Minimum Wing Mass
2. Asbaseline 1 with OJF = Minimum Wing Mass
3. As baseline 2 with OJF = Minimum TO Mass
4. As baseline 1with OJF = Minimum TO Mass
5. As baseline 2 with OJF = Minimum Fuel Mass
6. As baseline 1with OJF = Minimum Fuel Mass
7. As baseline 2 with OJF = Minimum DOC per Flight

Challenger Study (ref. Figure D8)

1.	Challenger Simulation Aspect Ratio	=	9.0	(48 seats)
2.	Challenger Simulation Aspect Ratio	=	Free	(48 seats)
3.	As Study 7 in Stretch Study above			(48 seats)
4.	Challenger Simulation Aspect Ratio	=	9.0	(68 seats)
5.	Challenger Simulation Aspect Ratio	=	Free	(68 seats)

In the descriptions above the study numbers are shown in italic, they are cross referenced in the full results contained i appendix D (the appropriate figure number for each study is referenced in the titles above).

Figure 5.1 (sheet 2) Initial Studies

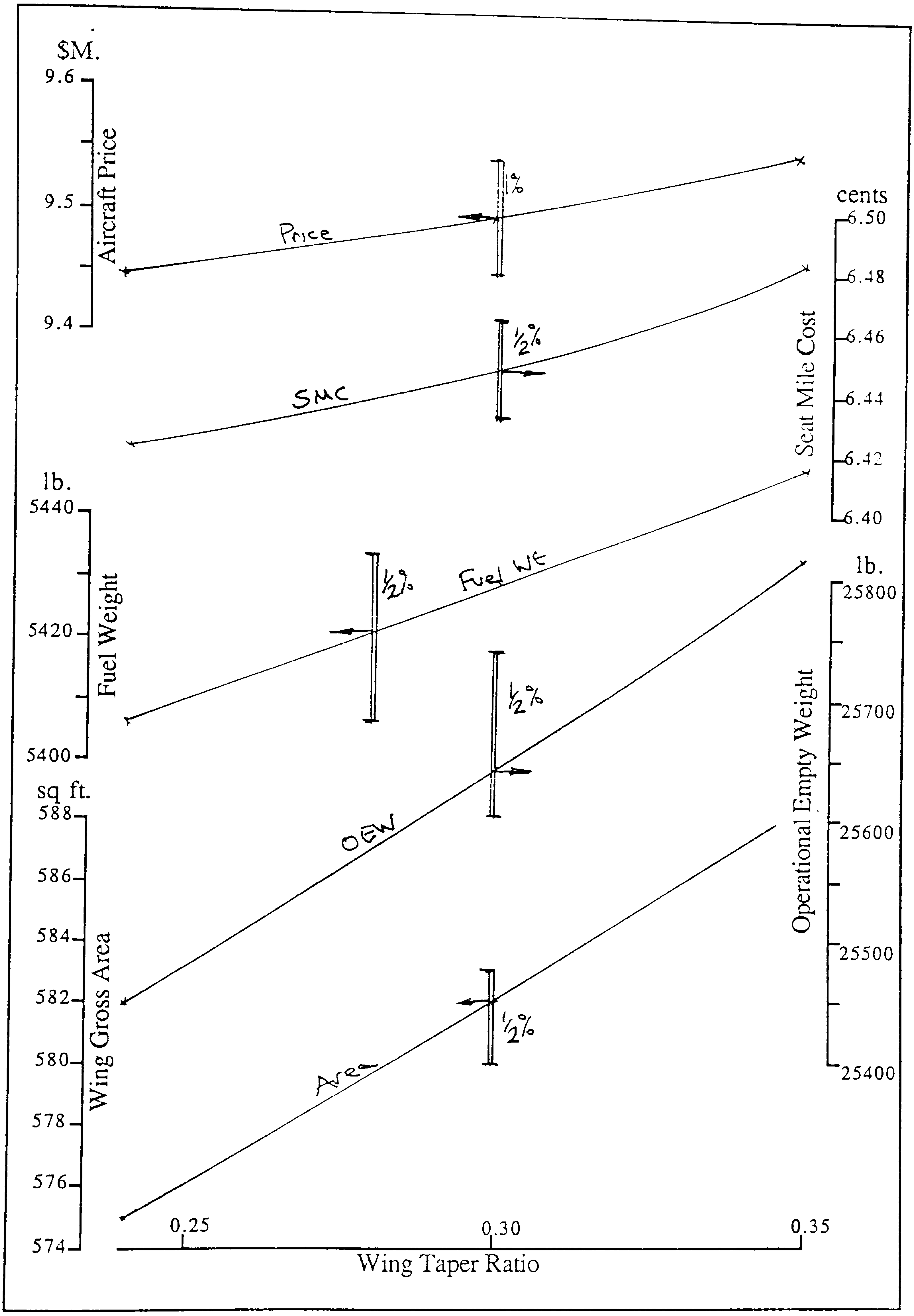


Figure 5.2 Taper Ratio Sensitivity (40 seats)
[1000 nm., 5300ft. BFL, 4600ft. LFL]

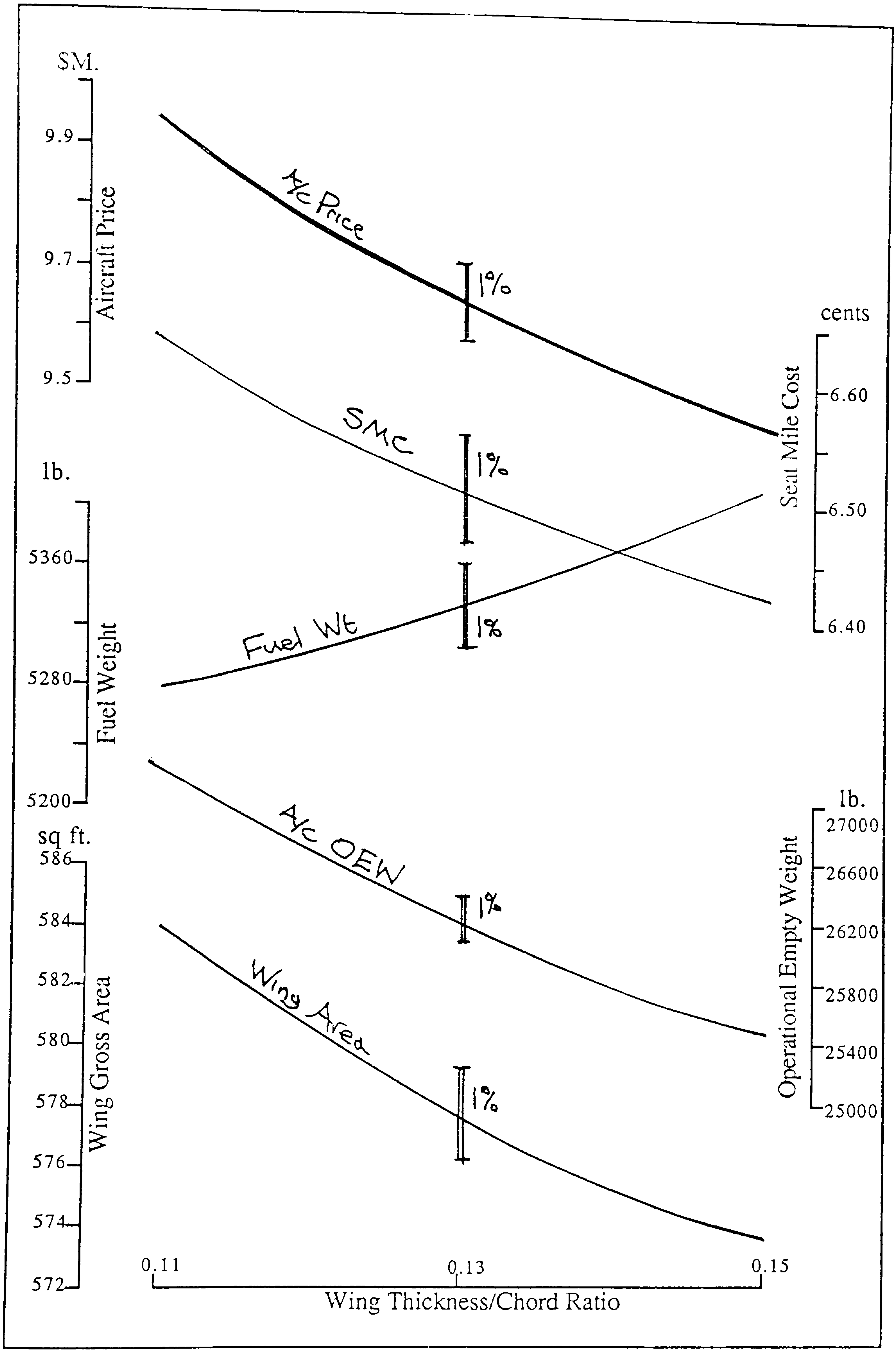


Figure 5.3 Wing Thickness/Chord Sensitivity (40 seats)
[1000 nm., 5300ft. BFL, 4600ft. LFL]

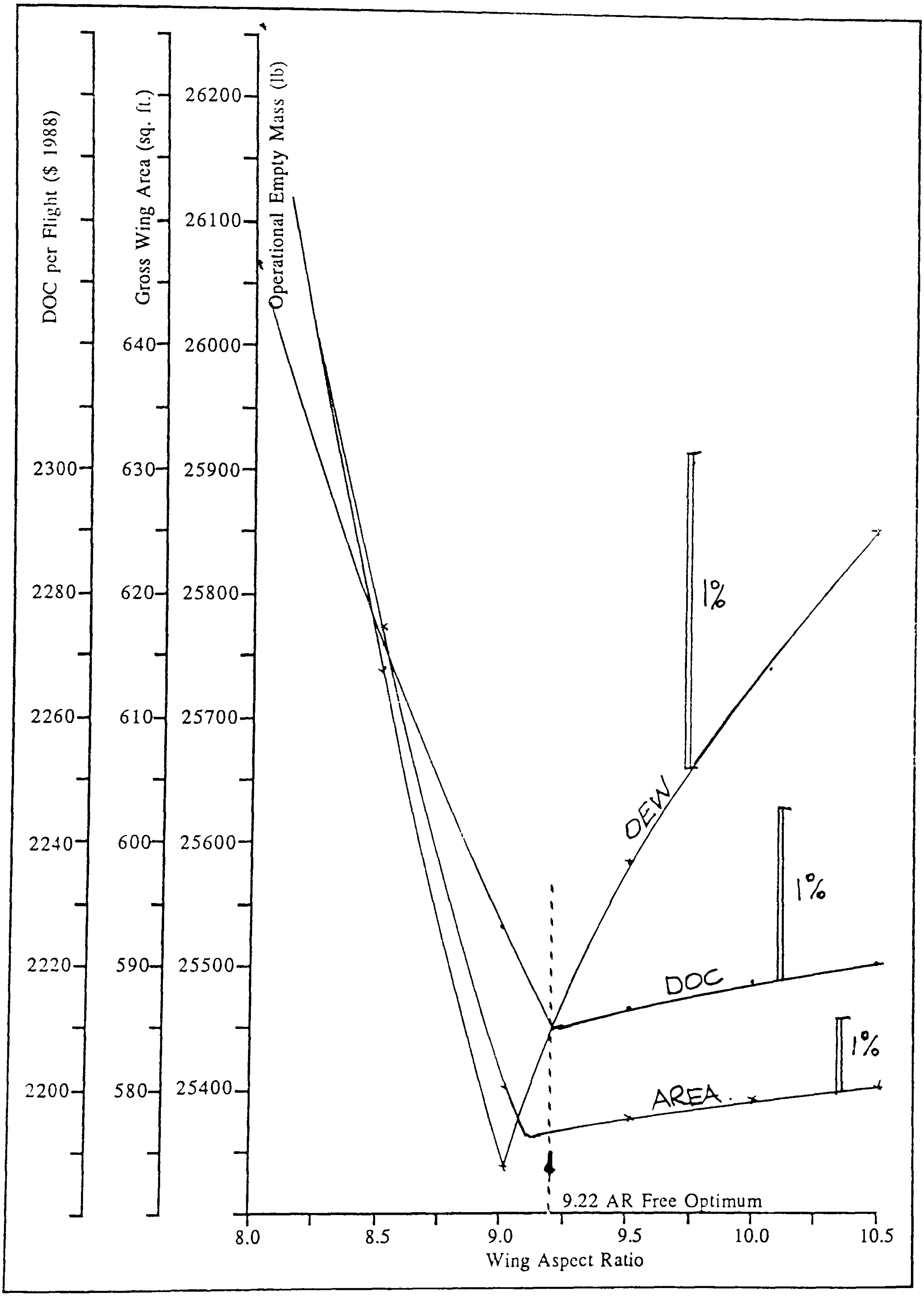


Figure 5.4 Wing Aspect Ratio Sensitivity Study

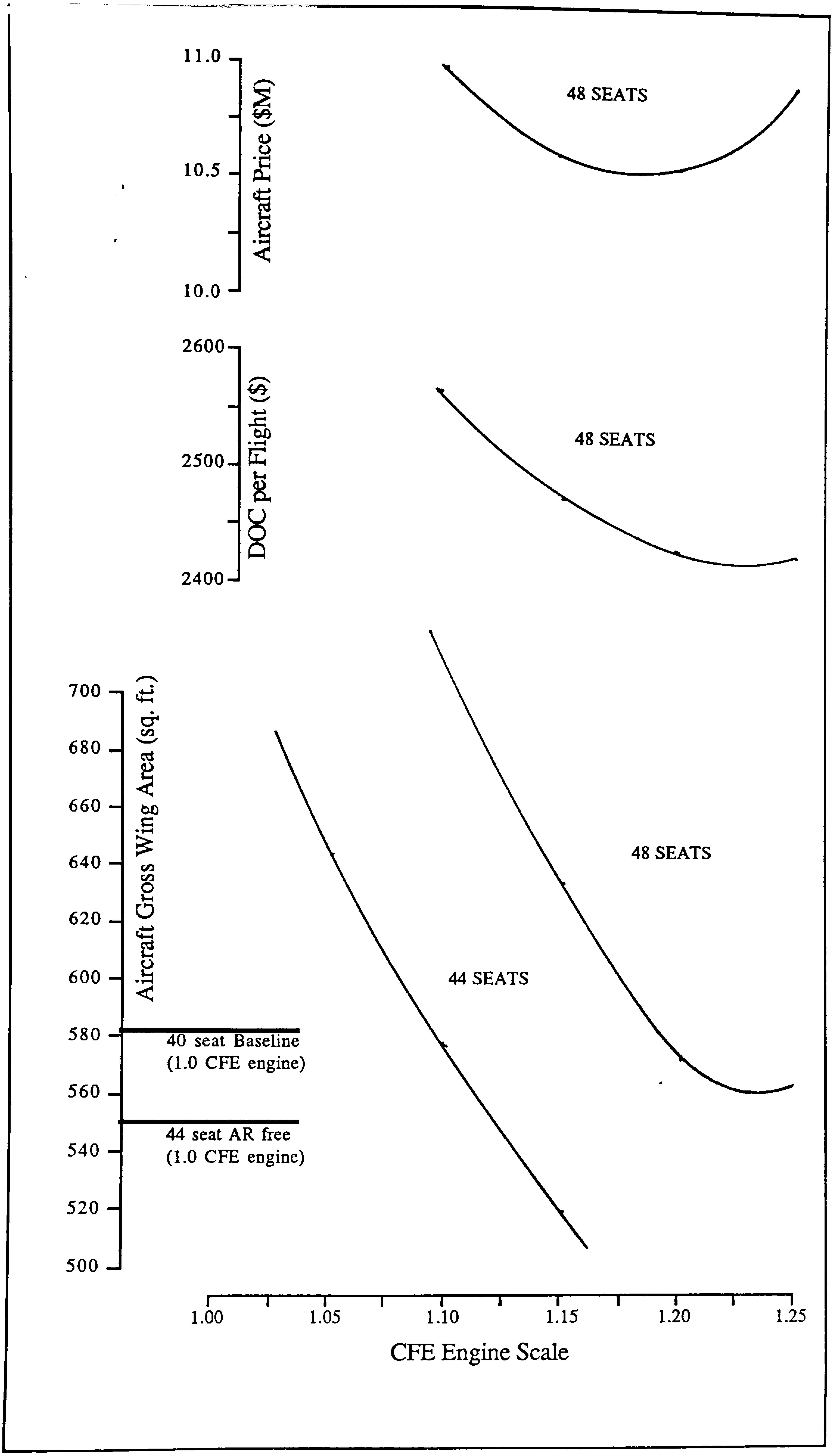


Figure 5.5 44/48 seat Stretch Studies
[1000 sm Stage, 5300ft. BFL = LFL]

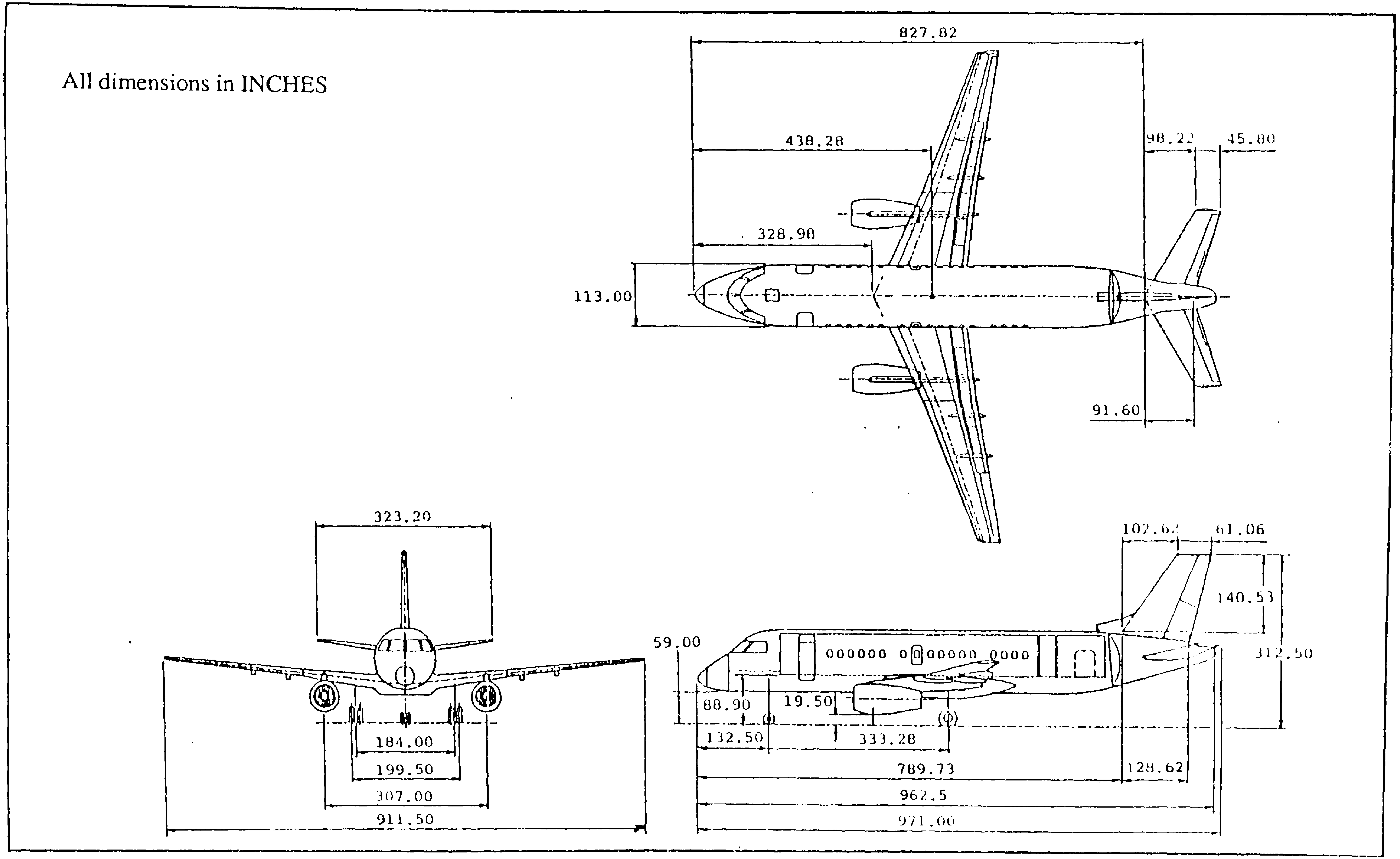


Figure 5.6 Shorts FJX Aircraft General Arrangement (Sept./1988)

Overall Dimensions (ft)

Overall Length	80.41
Overall Width	75.96
Overall Height	25.92
Ground Clearance	4.79

Wing Geometry (ft)

Gross Area		591.58
Span		74.22
Chord (smc)		7.98
Aspect Ratio		9.31
Thickness :	root	15.3%
	kink	12.3%
	tip	11.2%
Dihedral (deg)		6.0
Sweep	: Inner	21.5
(C/4)	Outer	18.8
Flap Area		95.0
Flap Movmt.(deg)		40.0

Tail Geometry (ft)

Horizontal surfaces

Gross Area	143.0
Span	25.92
Chord (smc)	5.52
Aspect Ratio	4.7
Thickness	11.6%
Sweep (deg)	27.0

Vertical surfaces

Gross Area	104.51
Height	12.52
Chord (smc)	8.35
Aspect Ratio	3.0
Thickness	11.6%
Sweep (deg)	31.39

Fuselage Geometry (ft)

Max length	80.2
Max Width	9.42
Max Depth	9.42
Cabin Length	39.59
Seat pitch (in.)	32.0

Performance (kts EAS)

V_A = 186

V_B = 187

V_C = 320/M.75

V_D = 400/M.83

V_S (clean) = 115.6

(TO) = 99.3

(land) = 89.9

Weights (lb)

Max.. TO	41300
Max Land.	40299
Max Z.F.	37500
Payload	10560
Cargo (alt.)	12500

Figure 5.7 Shorts FJX Aircraft Details (Sept/1988)

Landing Field Length Study (Ref. Figure D9)
(44 Seats, BFL = 5100 ft, Stage = 960 nm)

1[x]	LFL = 5100	AR = 9.27	5.	LFL = 4856	AR = 9.27
2.	LFL = 5003	AR = 9.27	6.	LFL = 4823	AR = 9.27
3.	LFL = 4921	AR = 9.27	7.	LFL = -	-
4.	LFL = 4888	AR = 9.27	8.	LFL = 5100	AR = Free

([x] baseline design)

Engine Stretch Study (CFE Engine, 44 Seats, (ref.figure D10))

1.	As baseline 1 above ,	engine scale = 1.00
3.	"	engine scale = 1.05
4.	"	engine scale = 1.10
5.	"	engine scale = 1.15

Flap Study (44 seats), (ref. figure D11)

1.	As baseline 1 above,	single slotted flaps (SSR
2.	"	double slotted flaps (DSF)
3.	"	DSF, engine scale = 1.05
4.	"	DSF, engine scale = 1.10
5.	"	DSF, engine scale = 1.15

56 Study (CFE engine, Field = 5700 ft),(ref. figure D12)

*1	Engine Scale	= 1.0, SSF	*5.	Engine scale	= 1.0, DSF
2	"	= 1.1, SSF	*6.	"	= 1.1, DSF
3.	"	= 1.2, SSF	7.	"	= 1.2, DSF
4.	"	= 1.3, SSF	8.	"	= 1.3, DSF

(*unfeasible designs)

68 Seat Study (CFE engine, Field = 6200 ft), (ref. figure D13)

* 1.	Engine Scale	= 1.2, SSF	*5.	Engine scale	= 1.2, DSF
2.		= 1.3, SSF	*6.		= 1.3, DSF
3.		= 1.4, SSF	7.		= 1.4, DSF
4.		= 1.5, SSF	8.		= 1.5, DSF

(*unfeasible designs)

Figure 5.8 (sheet 1) FJX Development Studies

44 Seats CFE and RR engine comparison (Field = 5100 ft), (ref. figure D14)

	1.	CFE engine scale	=	1.00, SSF
+	*2.*	CFE "	=	1.00, SSF
	3.	CFE "	=	1.00, DSF
	4.	CFE "	=	1.15, SSF
	5.	CFE "	=	1.15, DSF
	6.	RR "	=	1.00, SSF
+	*7*	RR "	=	1.00, SSF
	8.	RR "	=	1.00, DSF

(+ with landing field reduced to 4822 ft)

56 Seats CFE & RR engine comparison (field= 5700 ft), (ref.figure D15)

1.	CFE engine scale	=	1.2, SSF
2.	CFE "	=	1.3, SSF
3.	CFE "	=	1.2, DSF
4.	CFE "	=	1.3, DSF
5.	RR "	=	1.0, SSF
6.	RR "	=	1.1, SSF
7.	RR "	=	1.2, SSF

68 Seat CFE & RR engine comparison (field = 6200 ft), (ref.figure D16)

1.	CFE engine scale	=	1.4, SSF
2.	CFE "	=	1.5, SSF
3.	CFE "	=	1.4, DSF
4.	CFE "	=	1.5, DSF
5.	RR "	=	1.2, SSF
6.	RR "	=	1.3, SSF
7.	RR "	=	1.4, SSF
8.	RR "	=	1.5, SSF

In the descriptions above the study numbers are shown in italic, they can be cross referenced in appendix D (the appropriate figure number for each study is referenced in the titles above).

Figure 5.8 (Sheet 2) FJX Development Studies.

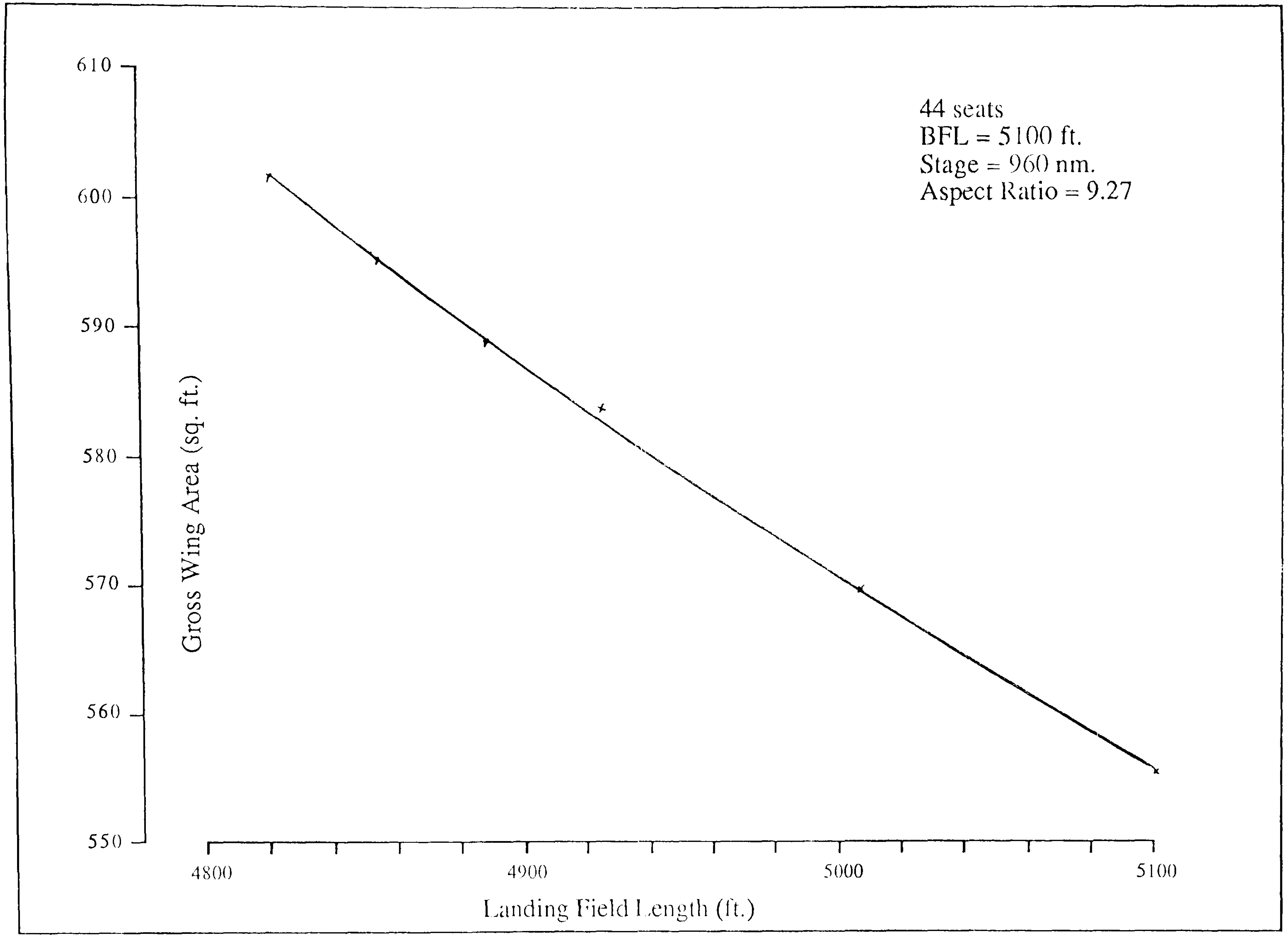


Figure 5.9 Effect of LFL on Optimum Wing Area

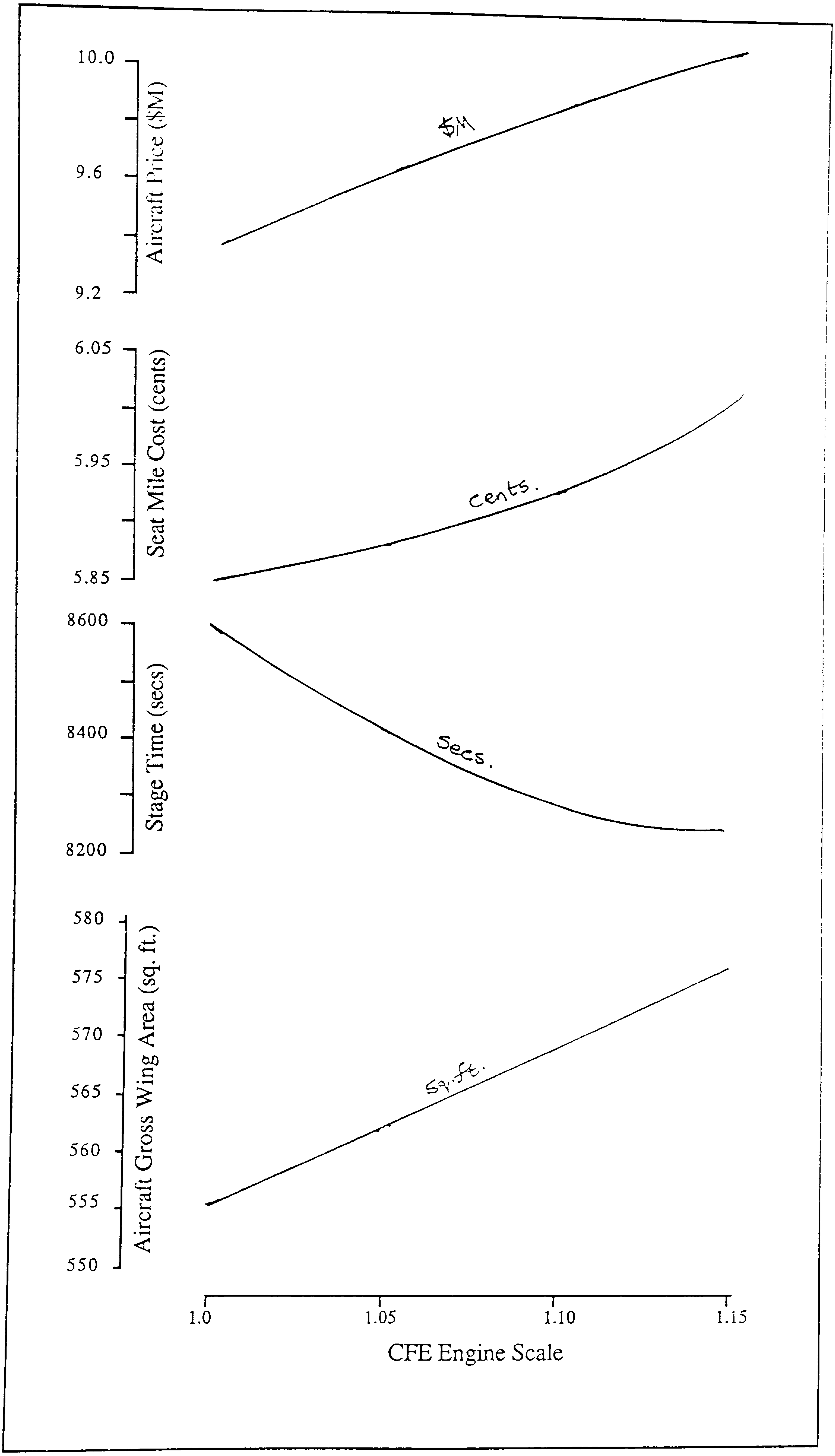


Figure 5.10 44 Seat Aircraft with Engine Stretch

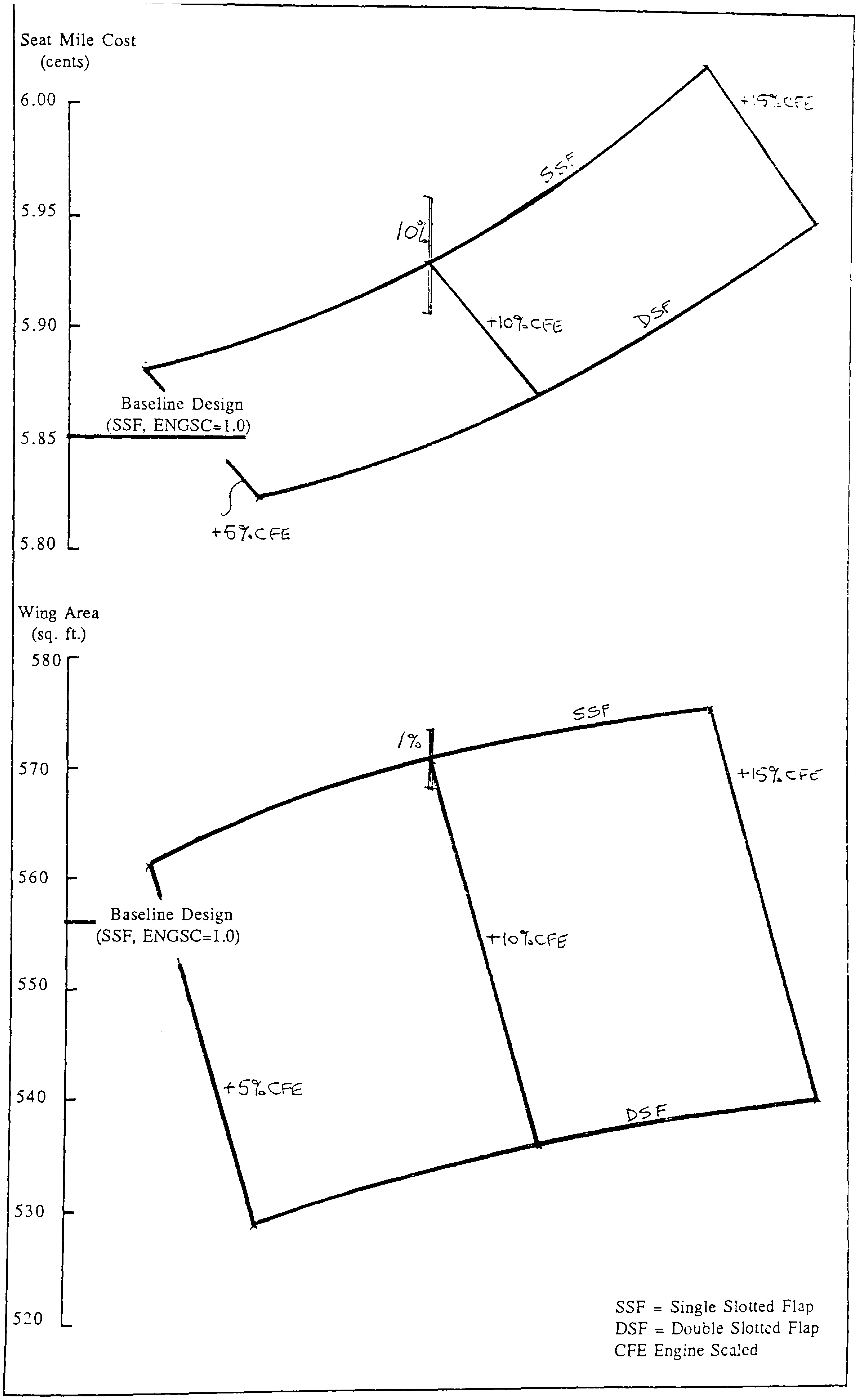


Figure 5.11 Engine & Flap Developments
[44seats, 960 nm., 5100 ft.]

(i) **Current RB581 Study (56 seats)**

Stage (sm) \ Field (ft)	5700	5900	6100
700	*1*	*5*	*9*
900	*2*	*6*	*10*
1100	*3*	*7*	*11*
1300	*4*	*8*	*12*

(ii) **Near-term RB580 Study (56 Seats, engine scale = 1.08**

Stage (sm) \ Field (ft)	5300	5500	5700	5900
700	*1*	*5*	*9*	*13*
900	*2*	*6*	*10*	*14*
1100	*3*	*7*	*11*	*15*
1300	*4*	*8*	*12*	*16*

(iii) **Far-term RB580 Study (eng. scale = 14.08) Field 6100 ft**

Stage (sm) \ Seats	68	72	76	80
1100	*1*	*5*	*9*	*13*
1300	*2*	*6*	*10*	*14*
1500	*3*	*7*	*11*	*15*
1700	*4*	*8*	*12*	*16*

(iii) **Far-term RB580 Study (eng. scale = 14.08) Field 6300 ft.**

Stage (sm) \ Seats	68	72	76	80
1100	*17*	*21*	*25*	*29*
1300	*18*	*22*	*26*	*30*
1500	*19*	*23*	*27*	*31*
1700	*20*	*24*	*28*	*32*

(iv) **Aspect Ratio Study (56 Seats, 900 Stage, 5700 field)**

1	AR = 8.8
2	= 9.0
3	= 9.2
4	= 9.4
5	= 9.6
6	= 9.8

7	AR = 10.0
8	= 10.2
9	= 10.4
10	= 10.6
11	= 10.8
12	= 11.0

Study numbers shown in italic above
Full results for each study are contained in figures D17(i), D18(ii), D19(iii) and D20(iv) in appendix D.

Figure 5.12 FJX/RR Stretch Studies

Figure 5.13 Aircraft Gross Wing Area (RB580, 56 seats)

Figure 5.14 Aircraft MTOW (RB580, 56 seats)

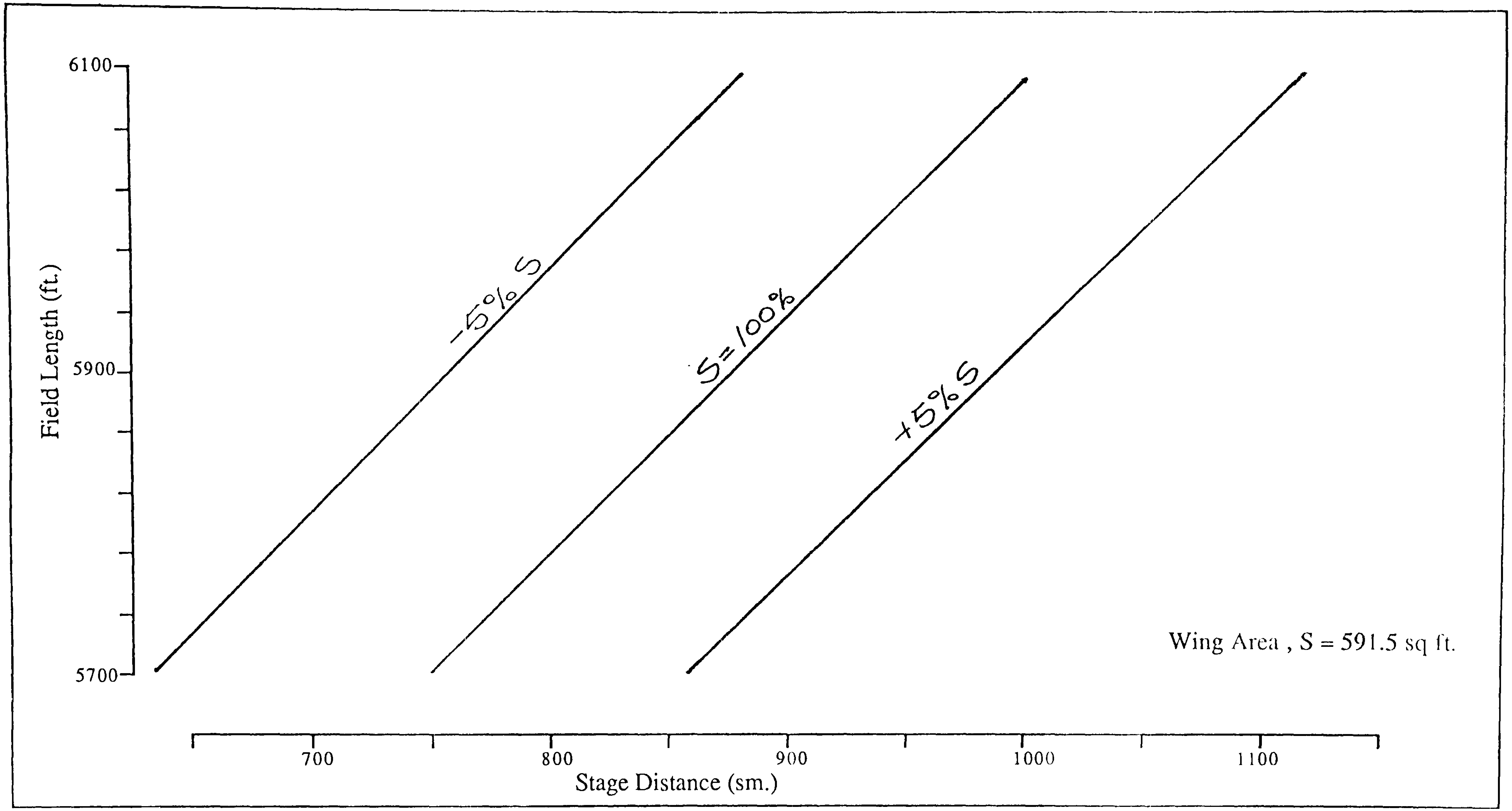


Figure 5.15 Stage / Field Trade-Offs with Wing Area (56 seats)

Figure 5.16 Aircraft MTOW (Near-term engine, 56 seats)

Figure 5.17 Aircraft Wing Area (Near-term engine, 56 seats)

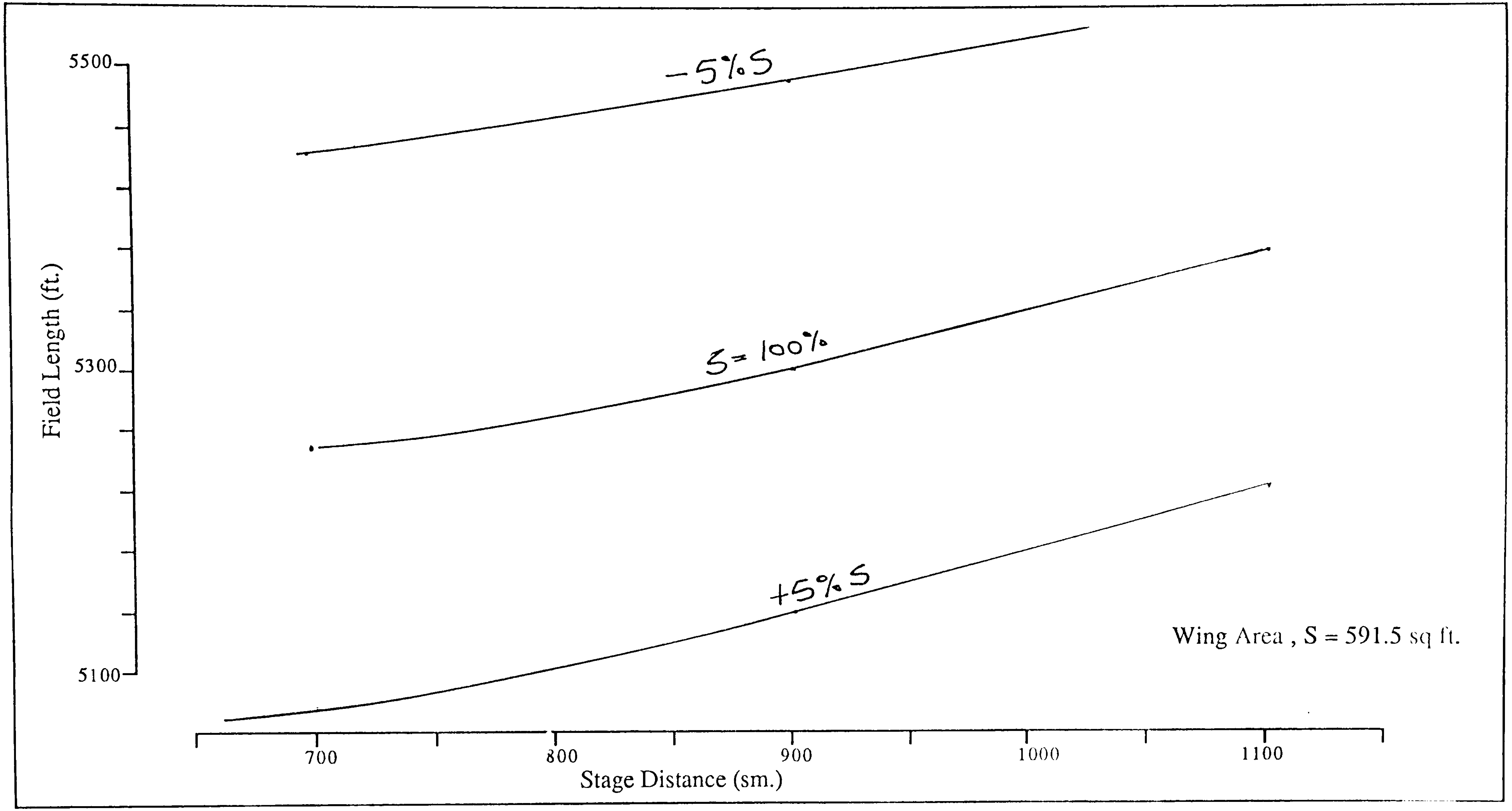


Figure 5.18 Stage / Field Trade-Offs with Wing Area (56 seats, Near-term Engine)

Figure 5.19 Aircraft Stretch Study [Far-term engine, 6100 ft.] (Max. TO. Weight)

Figure 5.20 Aircraft Stretch Study [Far-term engine, 6100 ft.] (Gross Wing Area)

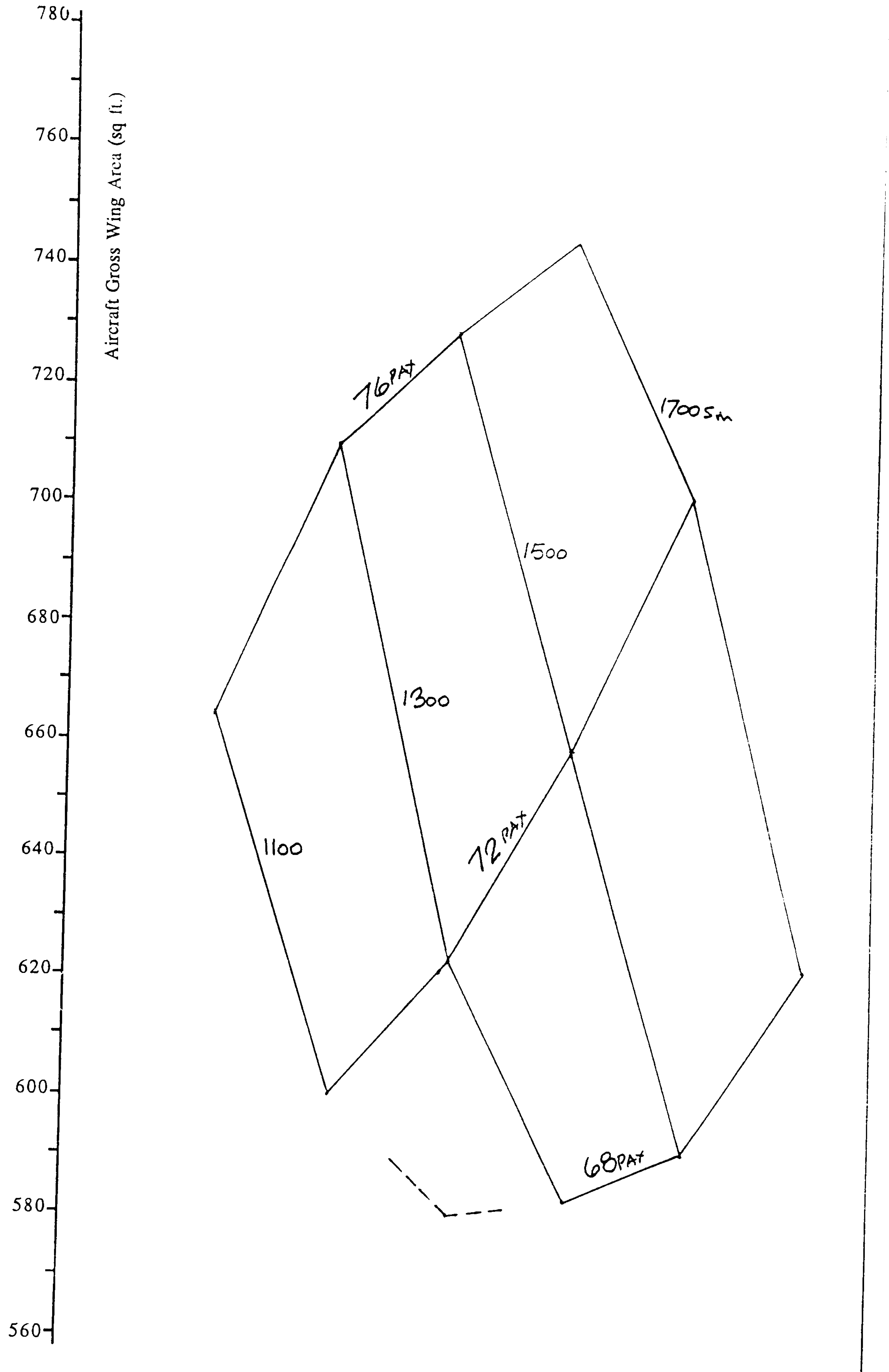


Figure 5.21 Aircraft Stretch Study [Far-term engine, 6300ft.] (Gross Wing Area)

Figure 5.22 Aircraft Stretch Study [Far-term engine, 6300ft.] (Max. TO. Weight)

Figure 5.23 Aspect Ratio Sensitivity Study (56 seats, 900sm., 5700ft.)

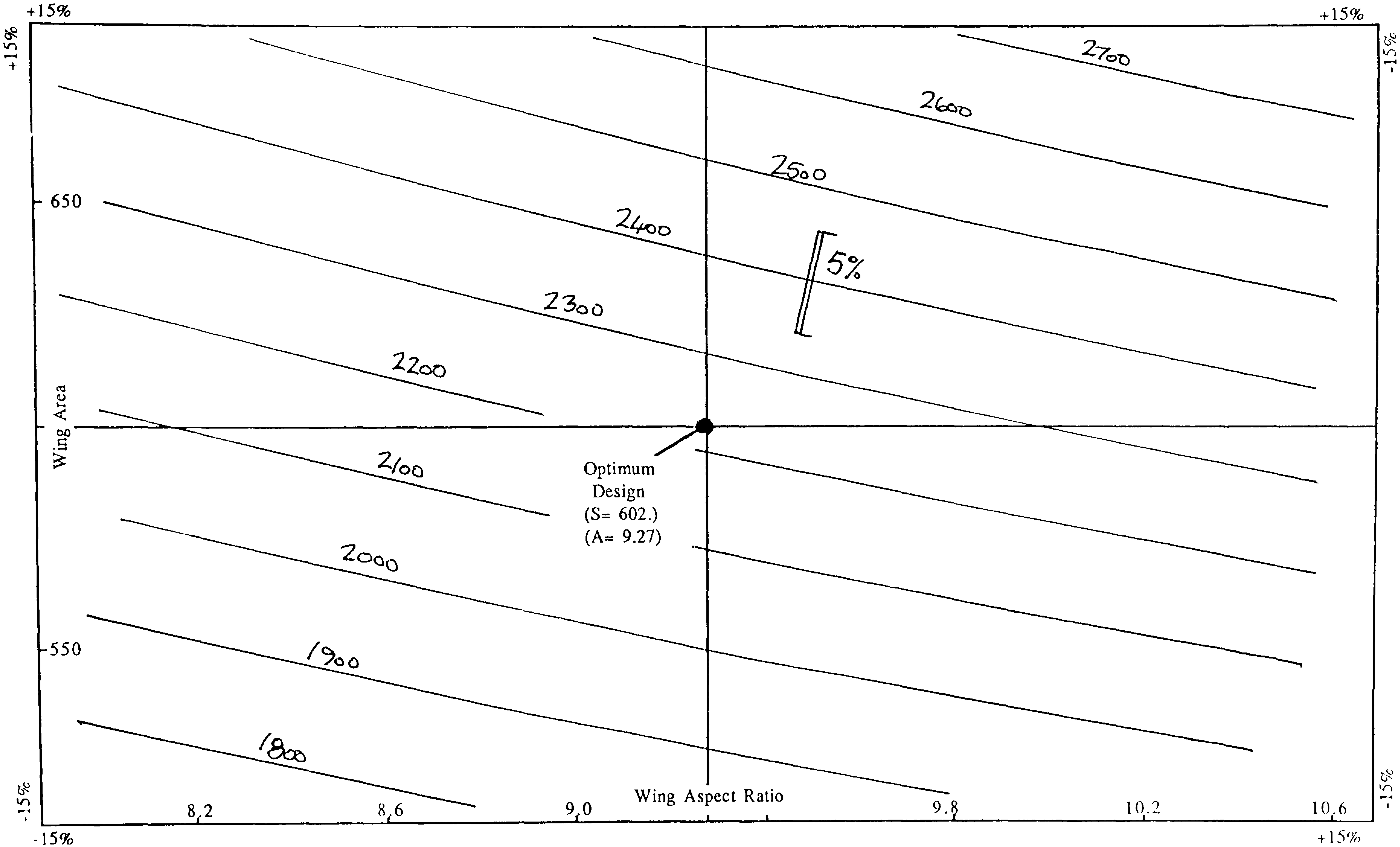


Figure 5.24 PERI-OPT Plot [Wing Mass (kg)]

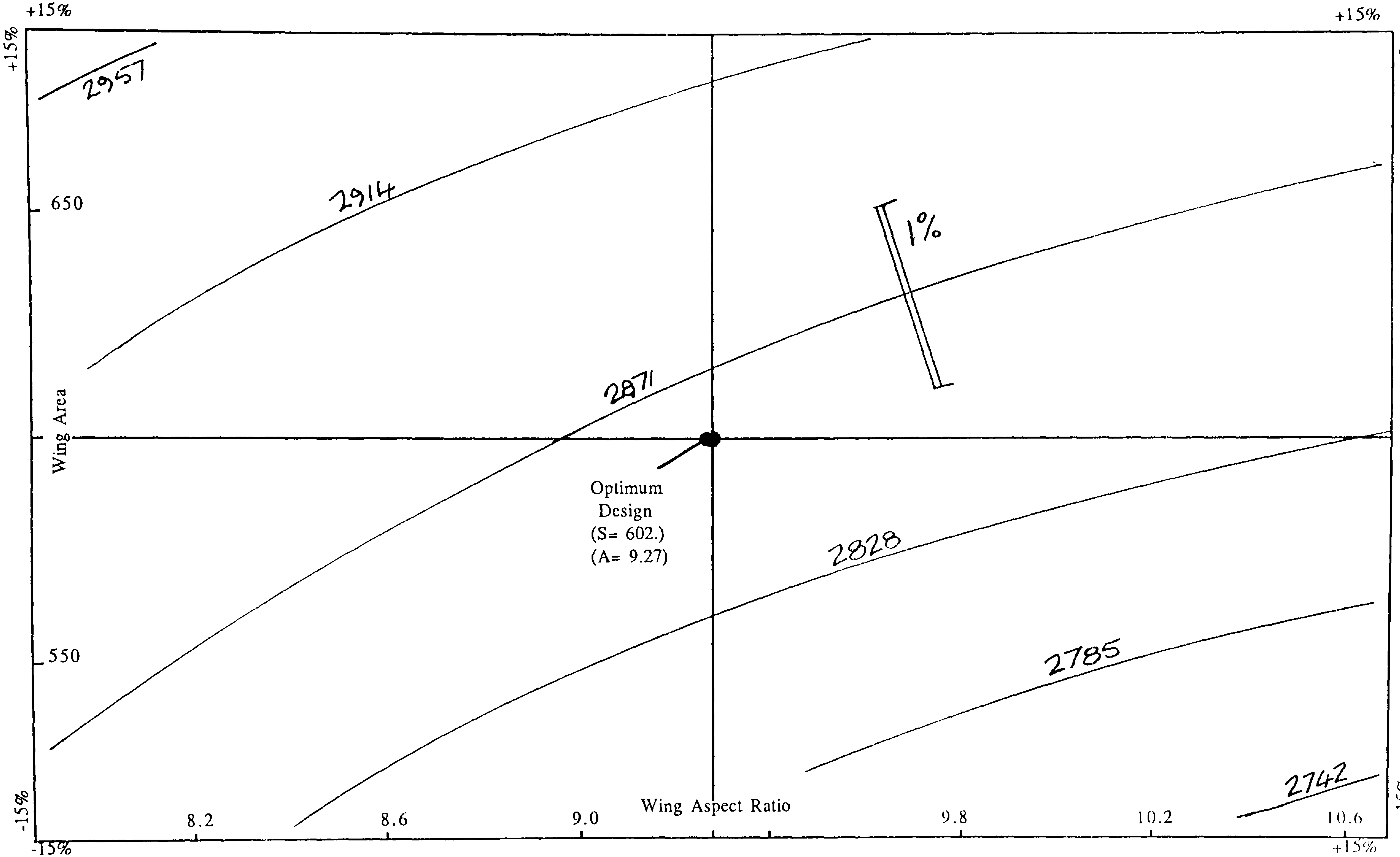


Figure 5.25 PERI-OPT Plot [Fuel Mass (kg)]

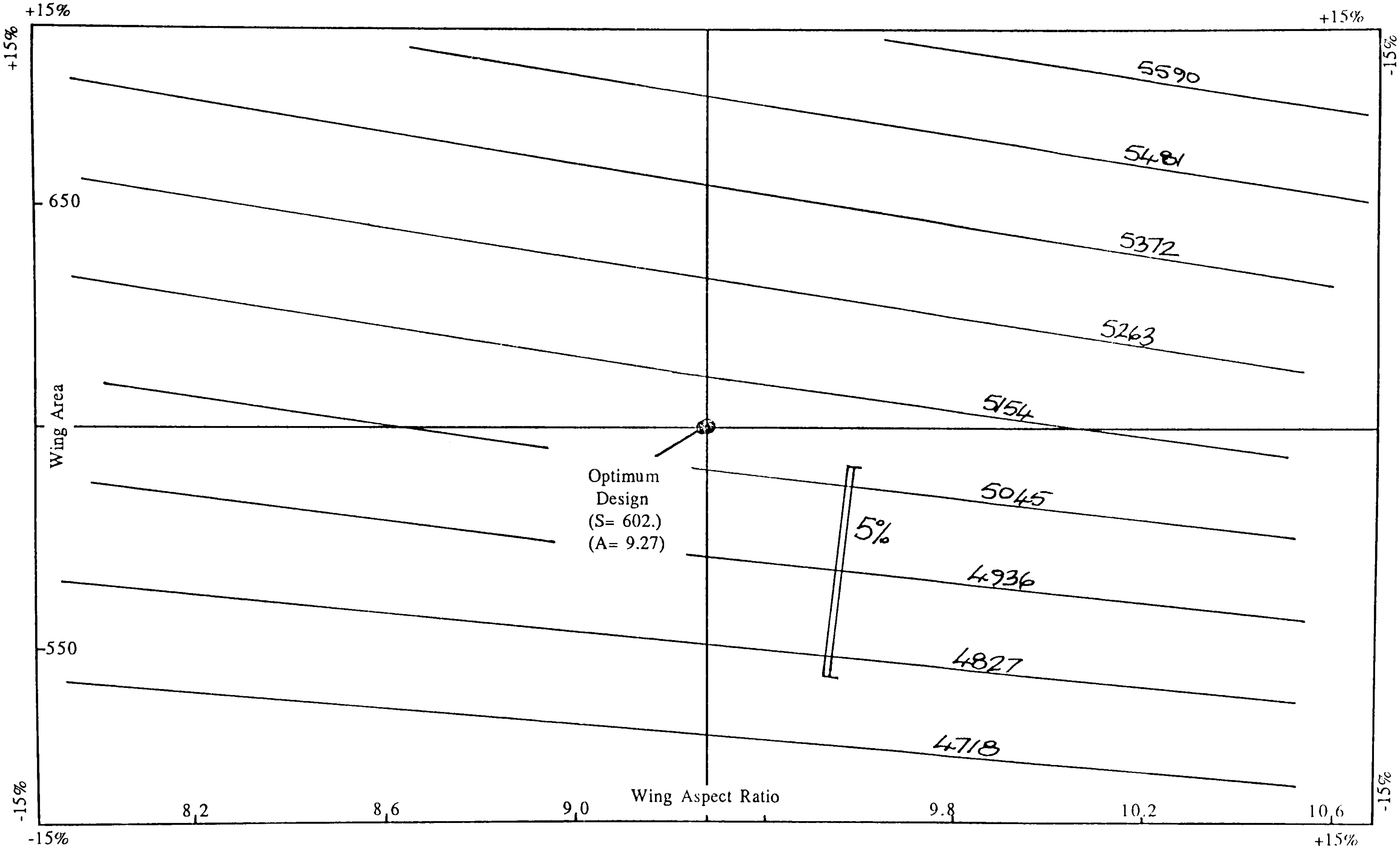


Figure 5.26 PERI-OPT Plot [Wing + Fuel Mass (kg)]

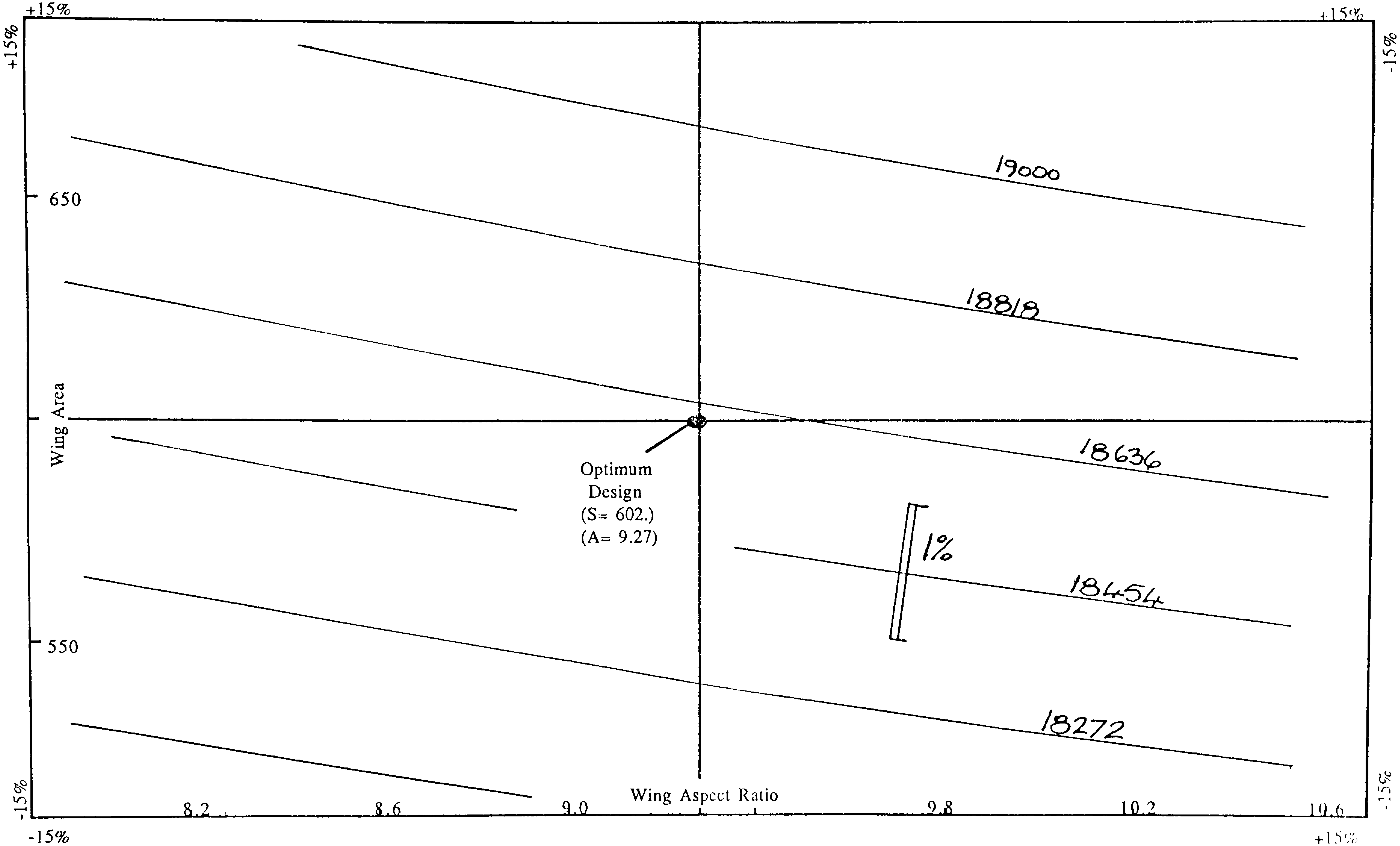


Figure 5.27 PERI-OPT Plot [Aircraft Empty Mass (kg)]

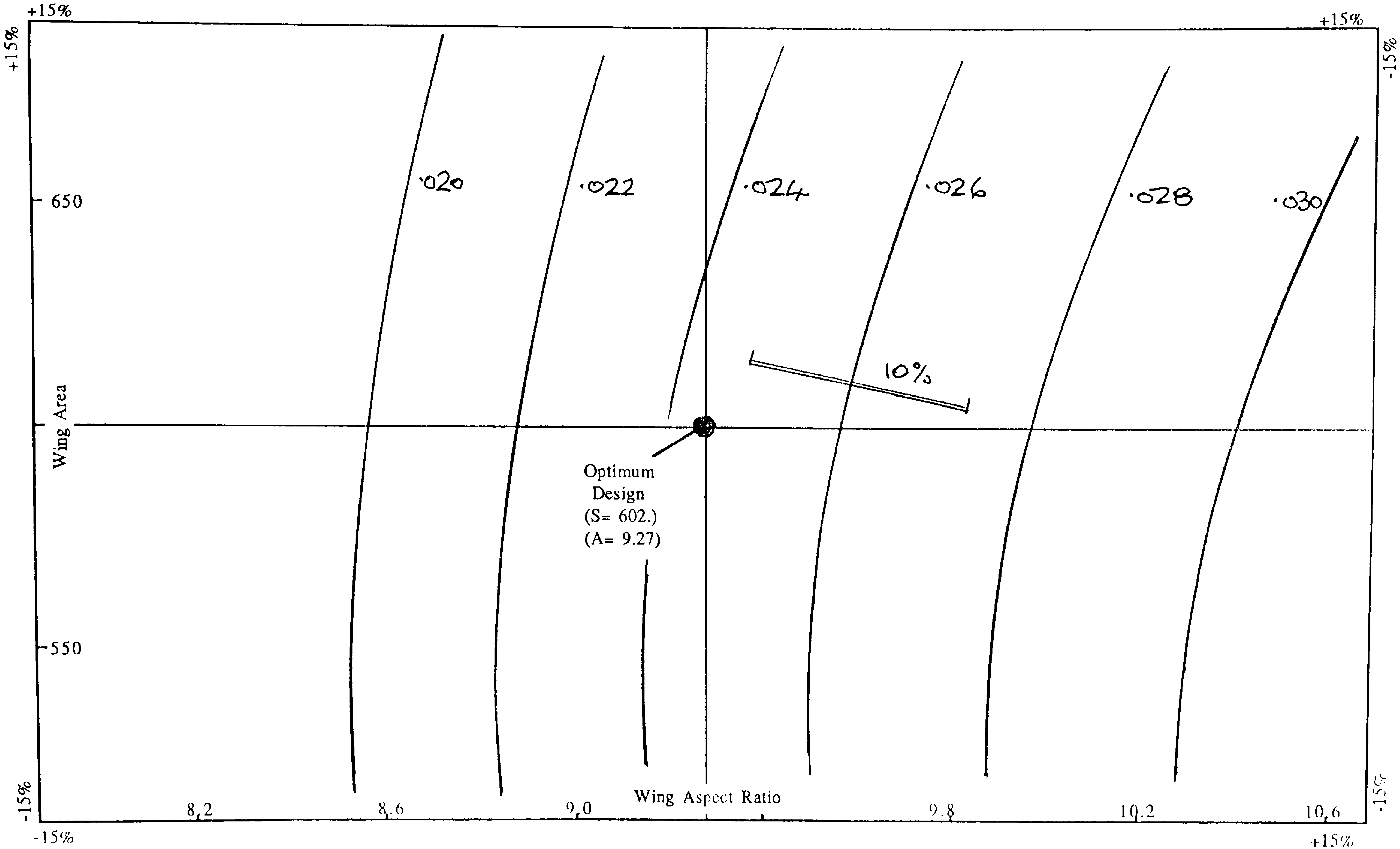


Figure 5.28 PERI-OPT Plot [WAT Gradient]

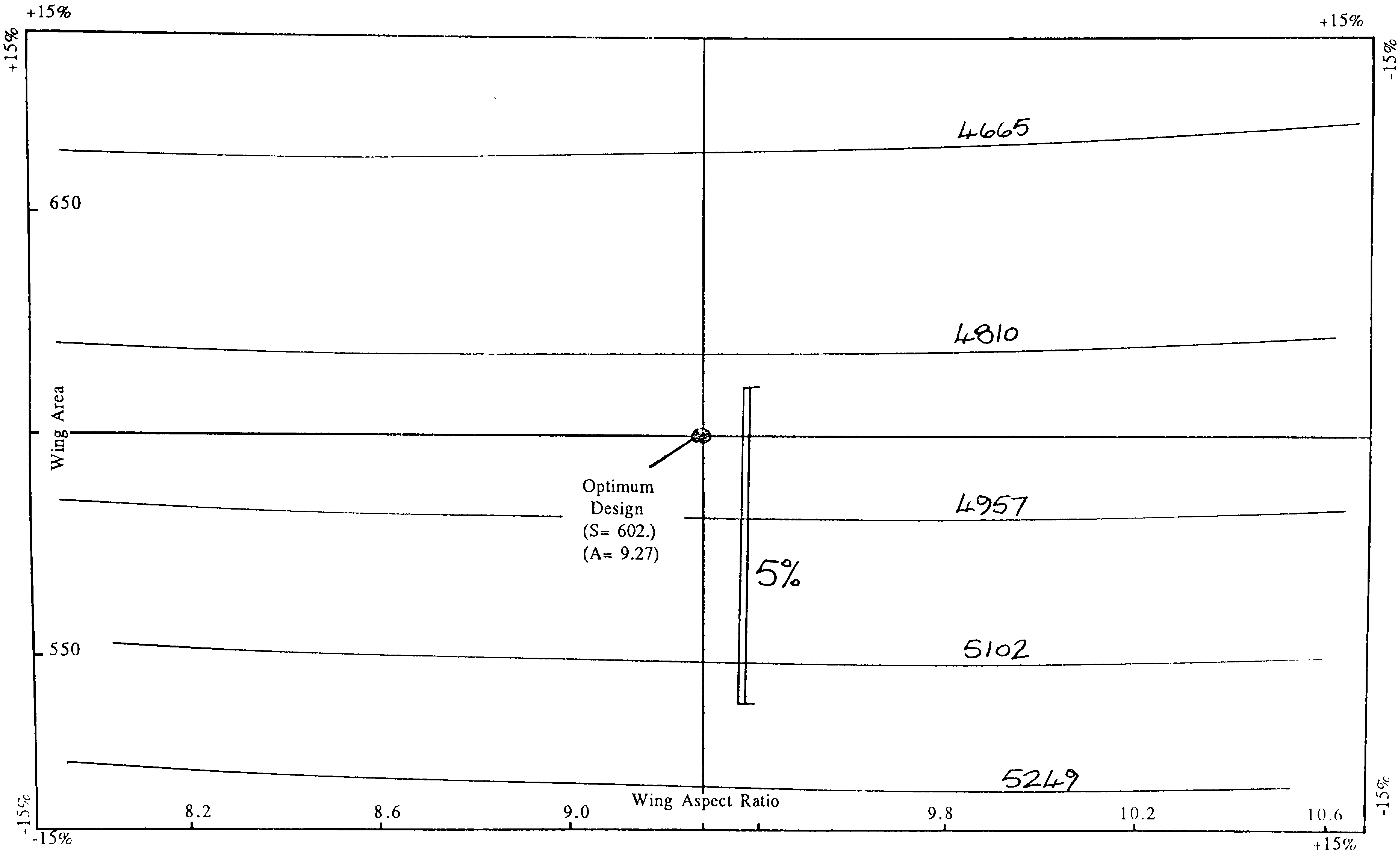


Figure 5.29 PERI-OPT Plot [Balanced Field Length (ft)]

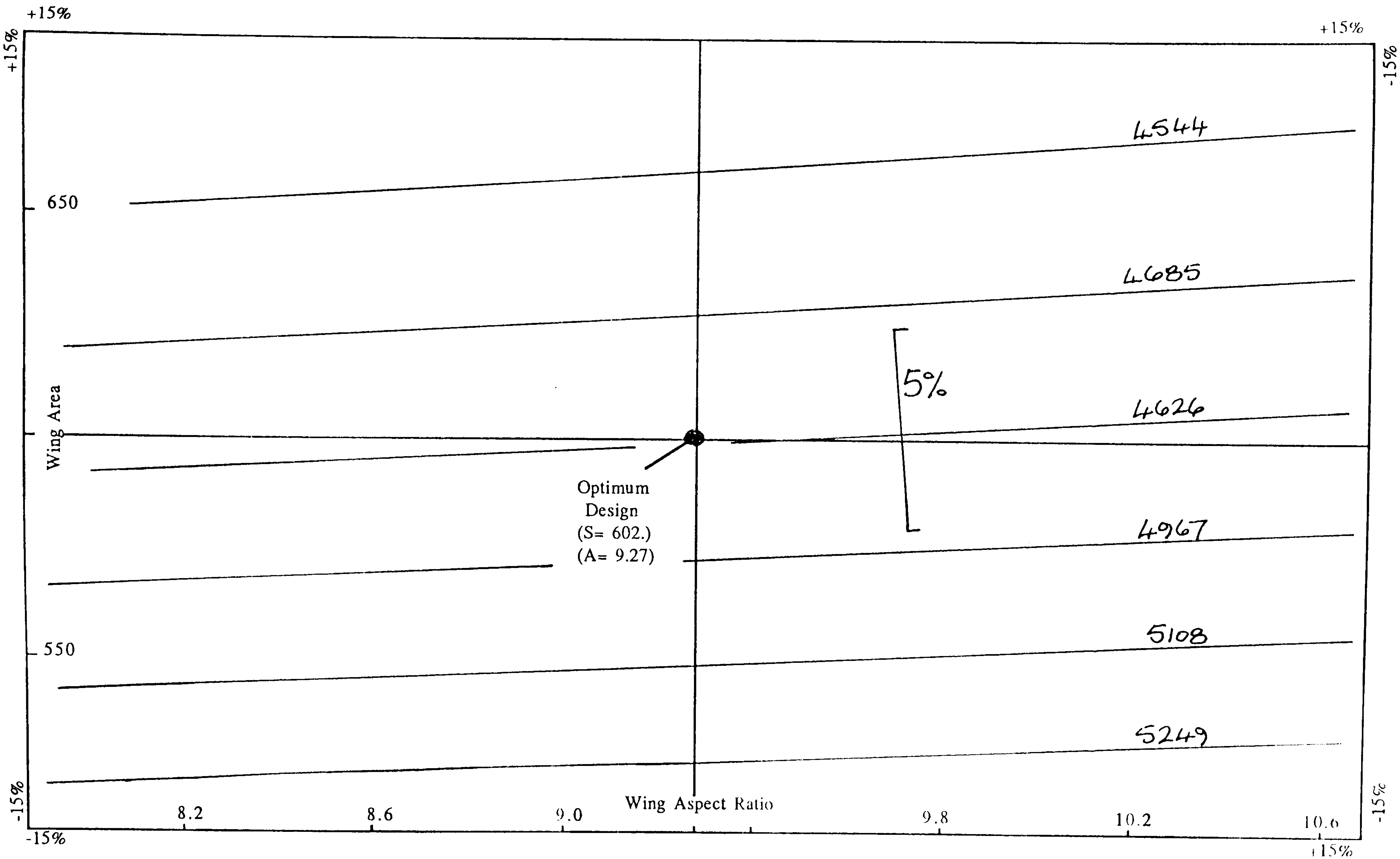


Figure 5.30 PERI-OPT Plot [Landing Field Length (ft)]

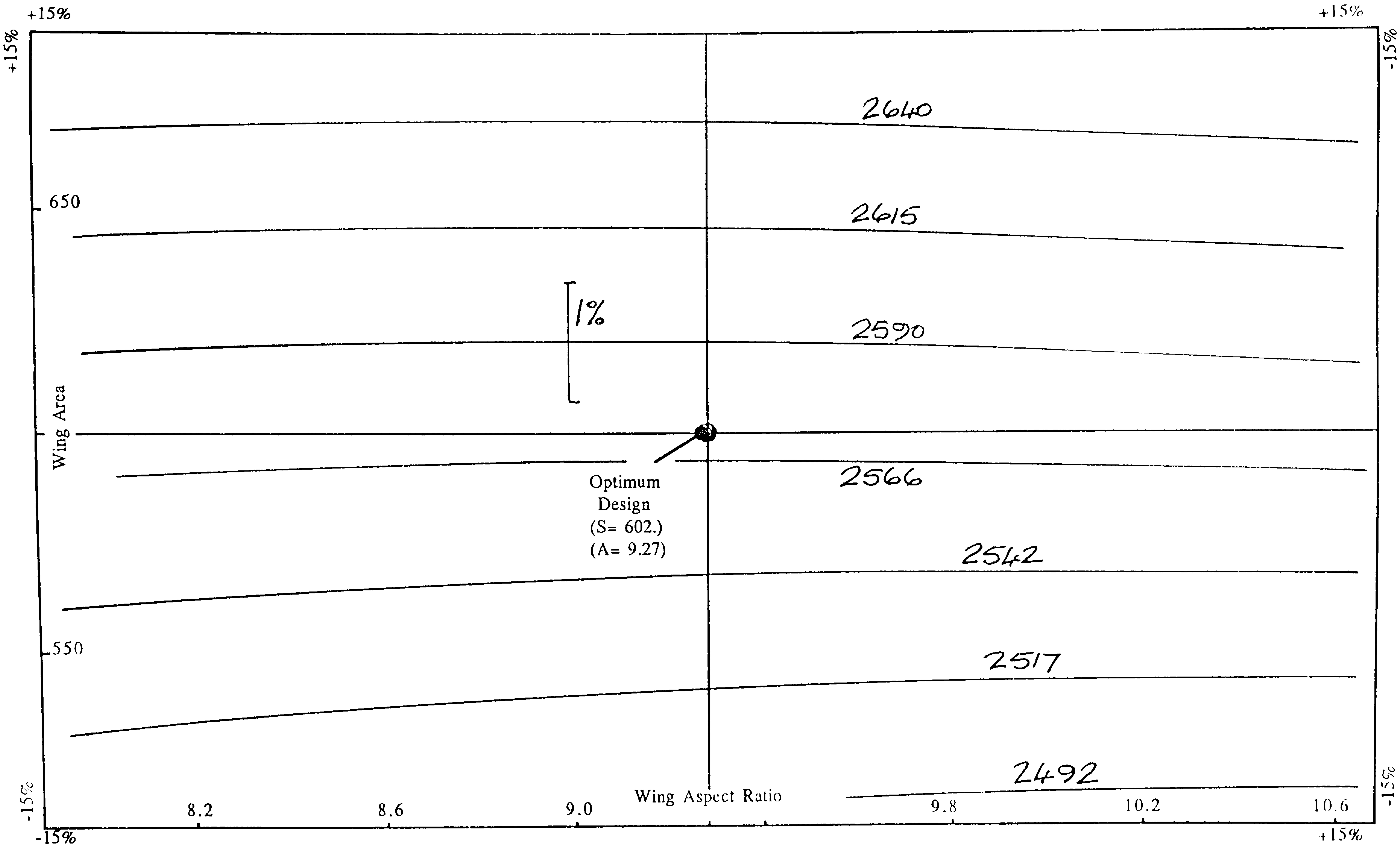


Figure 5.31 PERI-OPT Plot [Direct Operating Cost per Flight ($)]

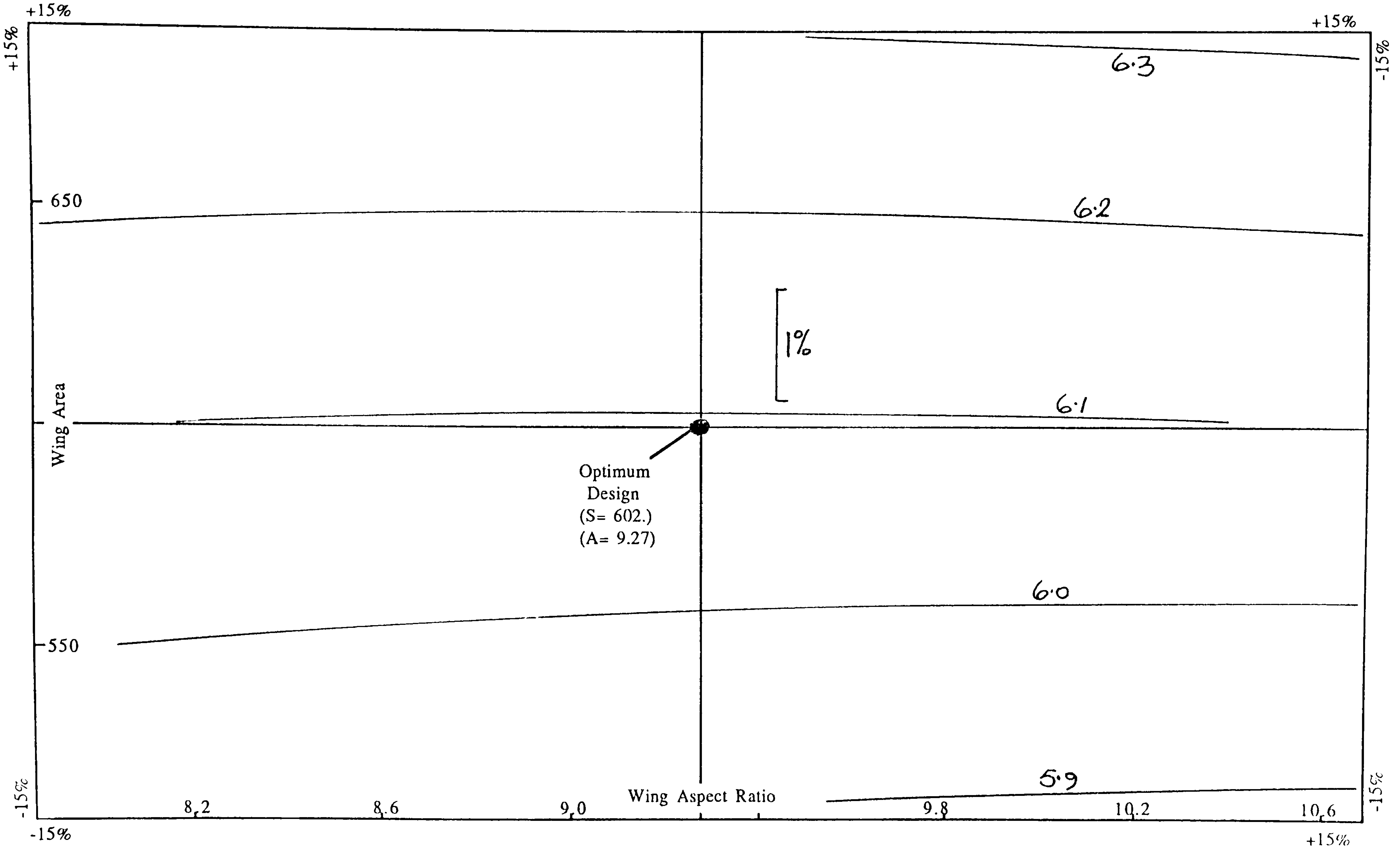


Figure 5.32 PERI-OPT Plot [Seat Mile Cost (cents)]

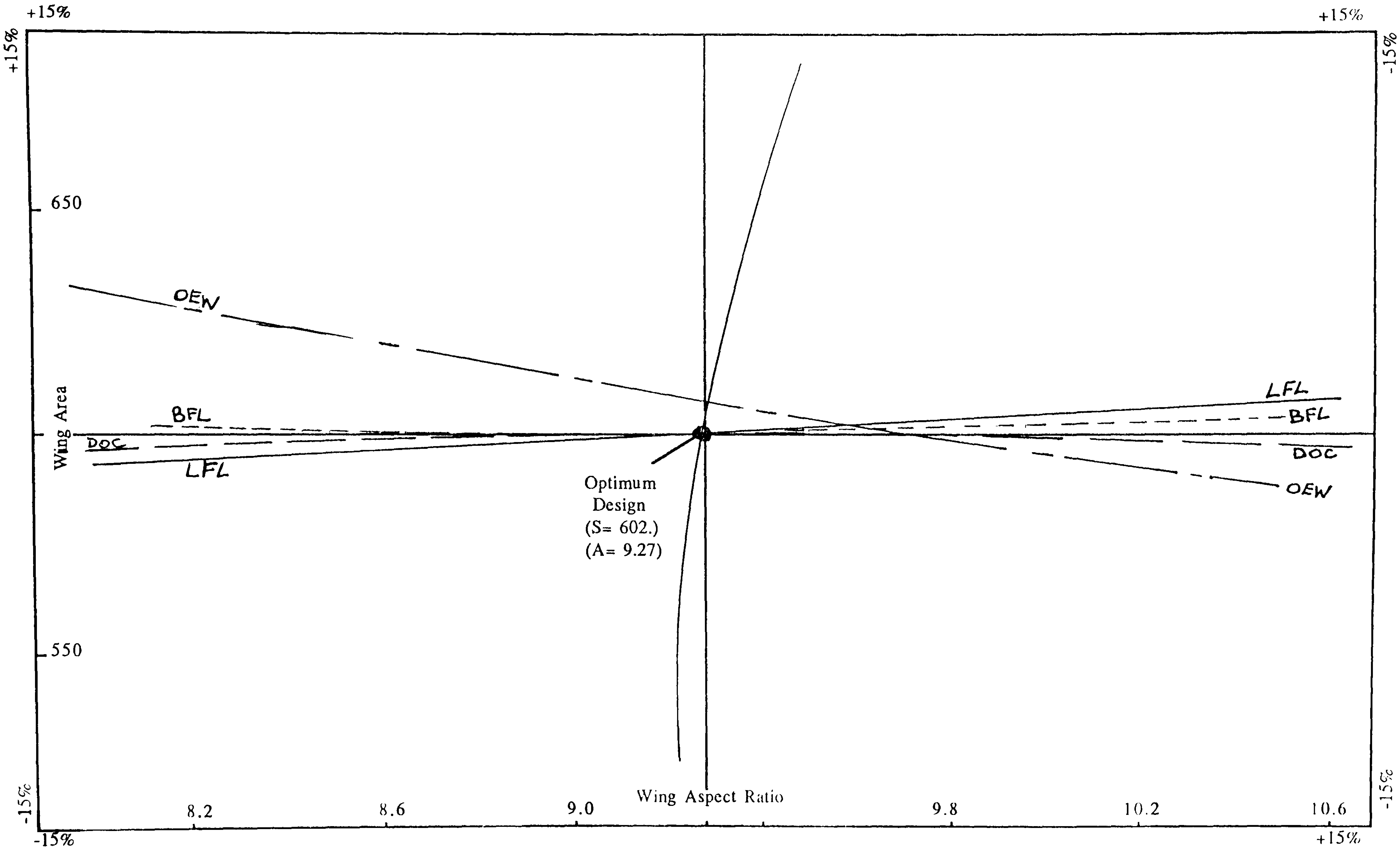


Figure 5.33 PERI-OPT Plot [Combined Criteria]

Generalised Design Studies (variable engine scale)

60 Seats

Stage (sm) \ Field (ft)	5800	6100	6400
1000	*1*	*2*	*3*
1250	*4*	*5*	*6*
1500	*7*	*8*	*9*

72 Seats

Stage (sm) \ Field (ft)	5800	6100	6400
1000	*1*	*2*	*3*
1250	*4*	*5*	*6*
1500	*7*	*8*	*9*

80 Seats

Stage (sm) \ Field (ft)	5800	6100	6400
1000	*1*	*2*	*3*
1250	*4*	*5*	*6*
1500	*7*	*8*	*9*

Study numbers for each size aircraft are shown in italic in the tables above.
The results are contained in figures D21, D22, D23 (appendix D)

The results are carpet plotted in figures:-

5.35 Engine scale
5.36 Gross wing area
5.37 Aircraft empty weight
5.38 Aircraft max. TO weight
5.39 Aircraft seat-mile costs

Figure 5.34 Generalised Design Studies

Figure 5.35 Generalised Design Study (Engine Scale)

Figure 5.36 Generalised Design Study (Wing Area)

Figure 5.37 Generalised Design Study (Empty Weight)

Figure 5.38 Generalised Design Study (MTOW)

Figure 5.39 Generalised Design Study (seat mile cost)

Mass Sensitivity Study (72 seats)
Effect of 5% reduction in operational empty weight

Field (ft) / Stage (sm)	5800	6100	6400
1000	*1*	*2*	*3*
1250	*4*	*5*	*6*
1500	*7*	*8*	*9*

Study numbers shown in italic in the table above refer to results shown in figure D24 (appendix D).

The results are plotted in Figure 5.41 together with similar results for an aircraft without the weight reduction effect added.

Figure 5.40 Mass Sensitivity Study

Figure 5.41 Weight Sensitivity Study (72 seats)

Variable Engine Study (80 seats)

Stage (sm) \ Field (ft)	5900	6100	6300	6500
900	*1*	2	*3*	*4*
1100	*5*	6	*7*	*8*
1300	9	*10*	*11*	*12*
1500	*13*	*14*	*15*	*16*
1700	*17*	*18*	*19*	*20*

Study numbers shown in italic in the above table, refer to results shown in figure D25 (appendix D).

Graphical presentation of some of the results is shown in the following figures:-

5.43 Engine scale
5.44 Gross wing area
5.45 Aircraft empty weight
5.46 Aircraft maximum take-off weight
5.47 Direct operating cost per flight
5.48 Aircraft seat mile cost

Results for the aspect ratio study are shown in figure D26 (appendix D) and plotted in the following figures:-

5.49 Engine scale
5.50 Gross wing area
5.51 Aircraft empty weight
5.52 DOC per flight
5.53 Aircraft MTO weight

Figure 5.42 Variable Engine Study

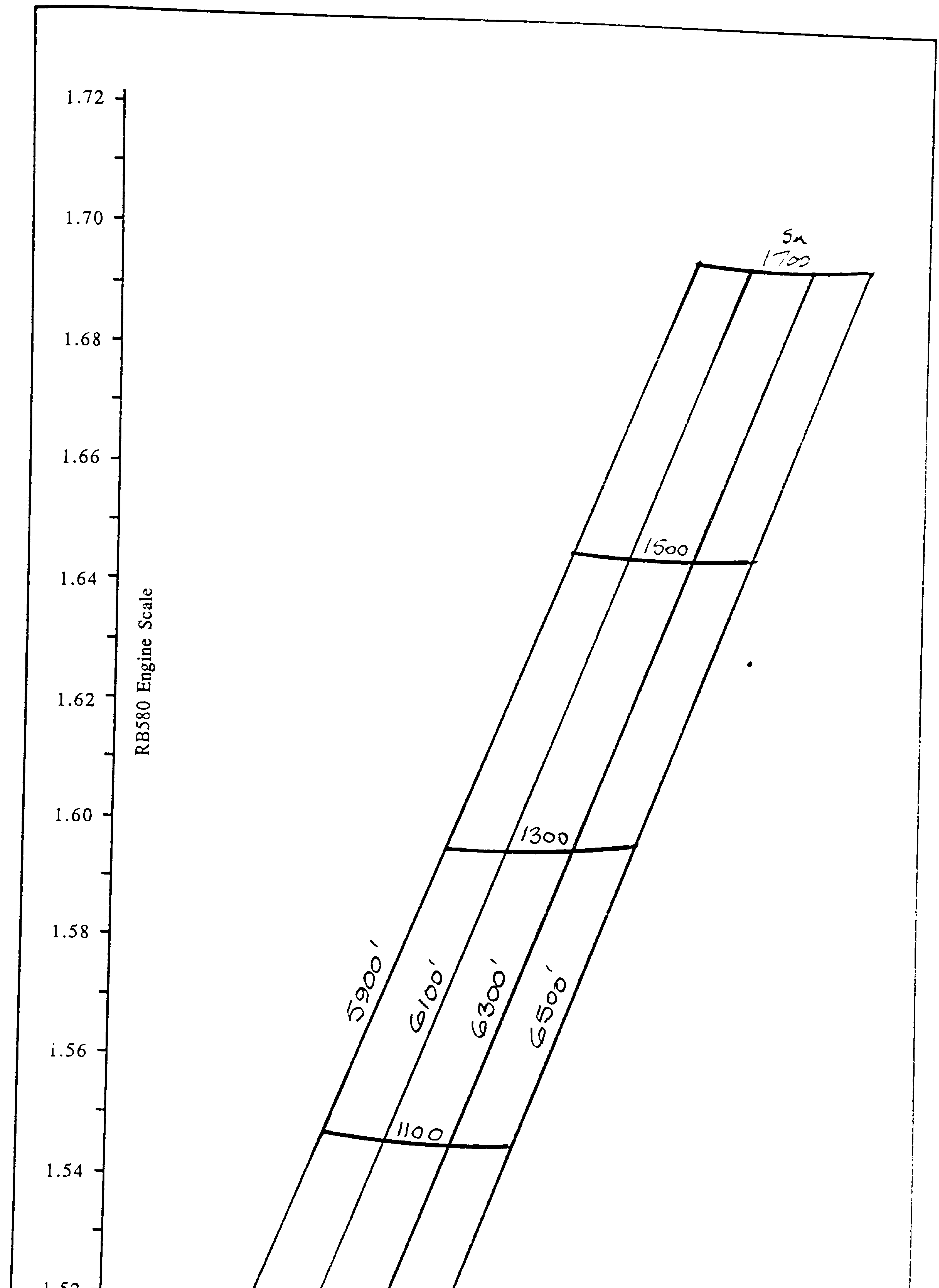


Figure 5.43 RB580 Engine Scale (80 seats)

Figure 5.44 Gross Wing Area (80 seats)

Figure 5.45 Aircraft Empty Weight (80 seats)

Figure 5.46 Aircraft MTO Weight (80 seats)

Figure 5.47 DOC.per Flight (80 seats)

Figure 5.48 Aircraft Seat-Mile Cost (80 seats)

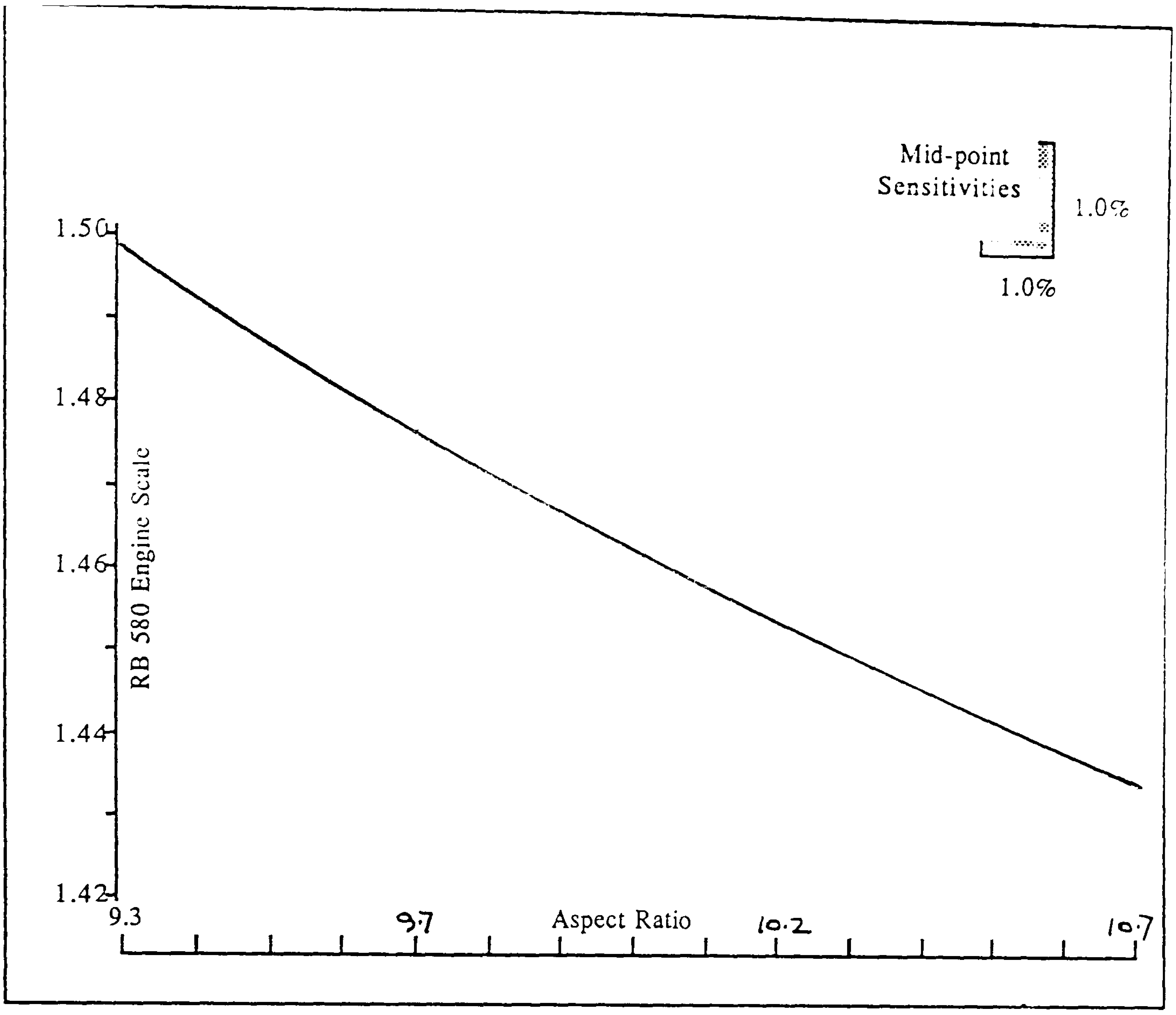


Figure 5.49 Engine Scale vs. Wing Aspect Ratio

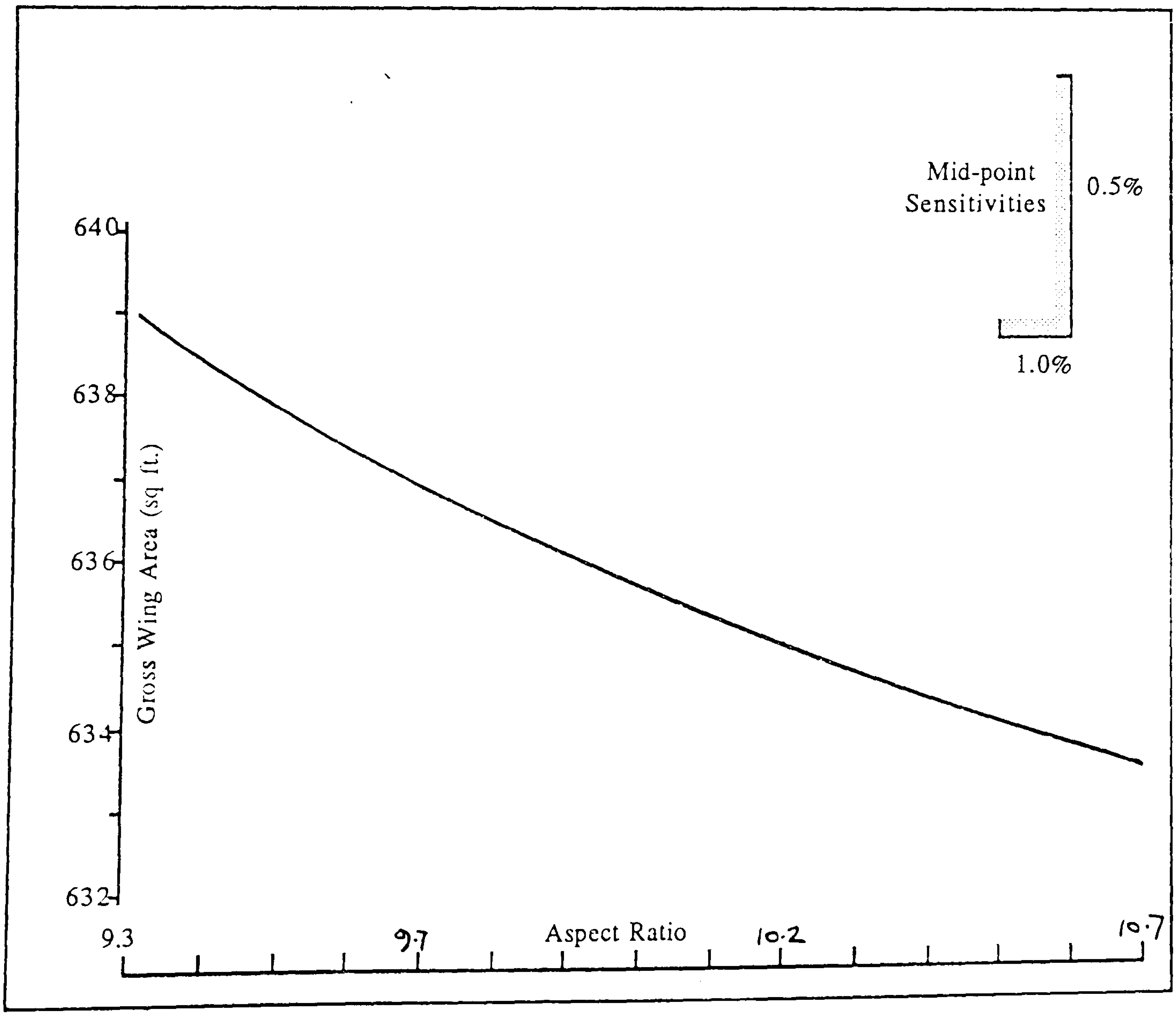


Figure 5.50 Wing Area vs. Wing Aspect Ratio

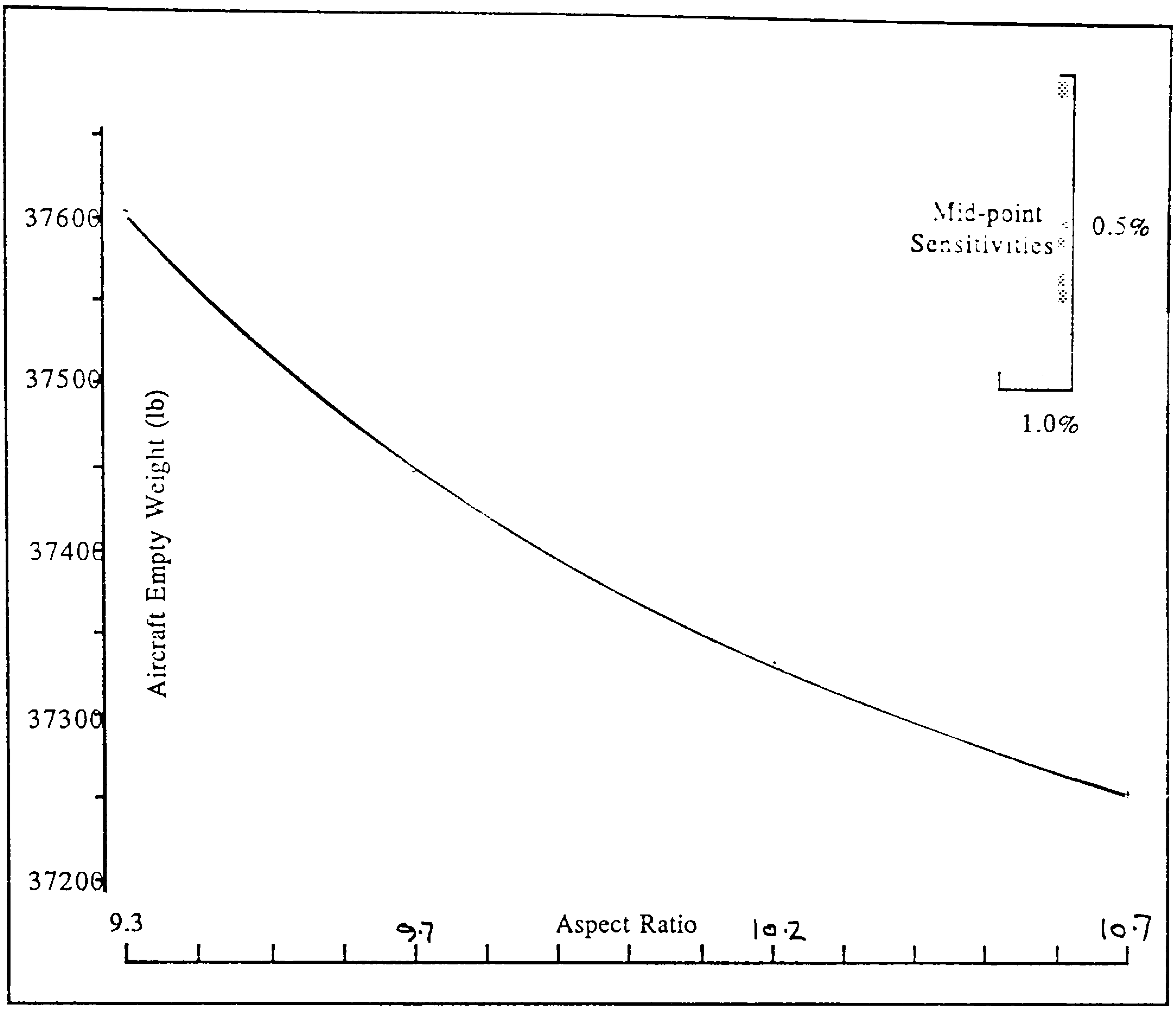


Figure 5.51 Empty Weight vs. Wing Aspect Ratio

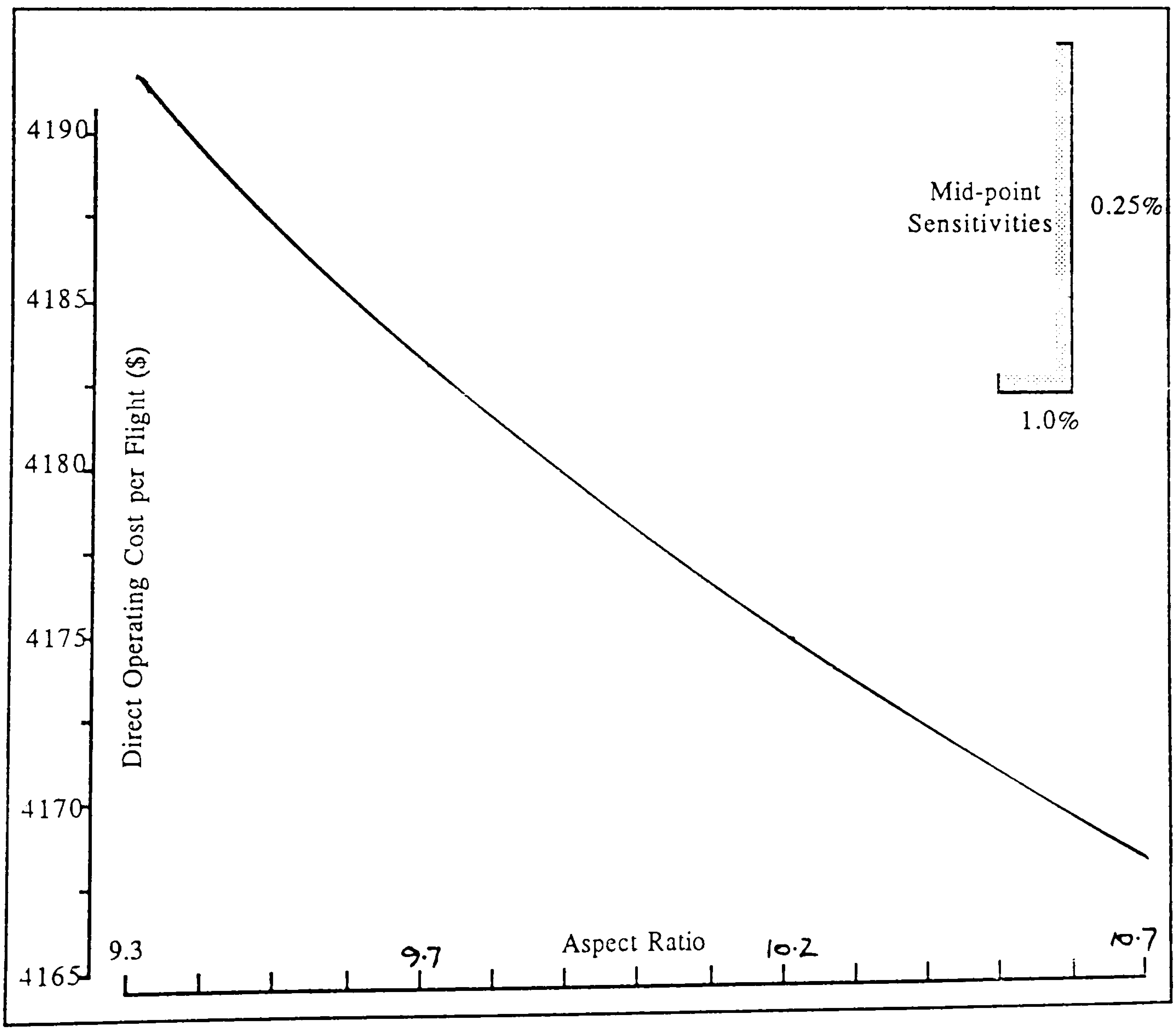


Figure 5.52 Aircraft DOC. vs. Wing Aspect Ratio

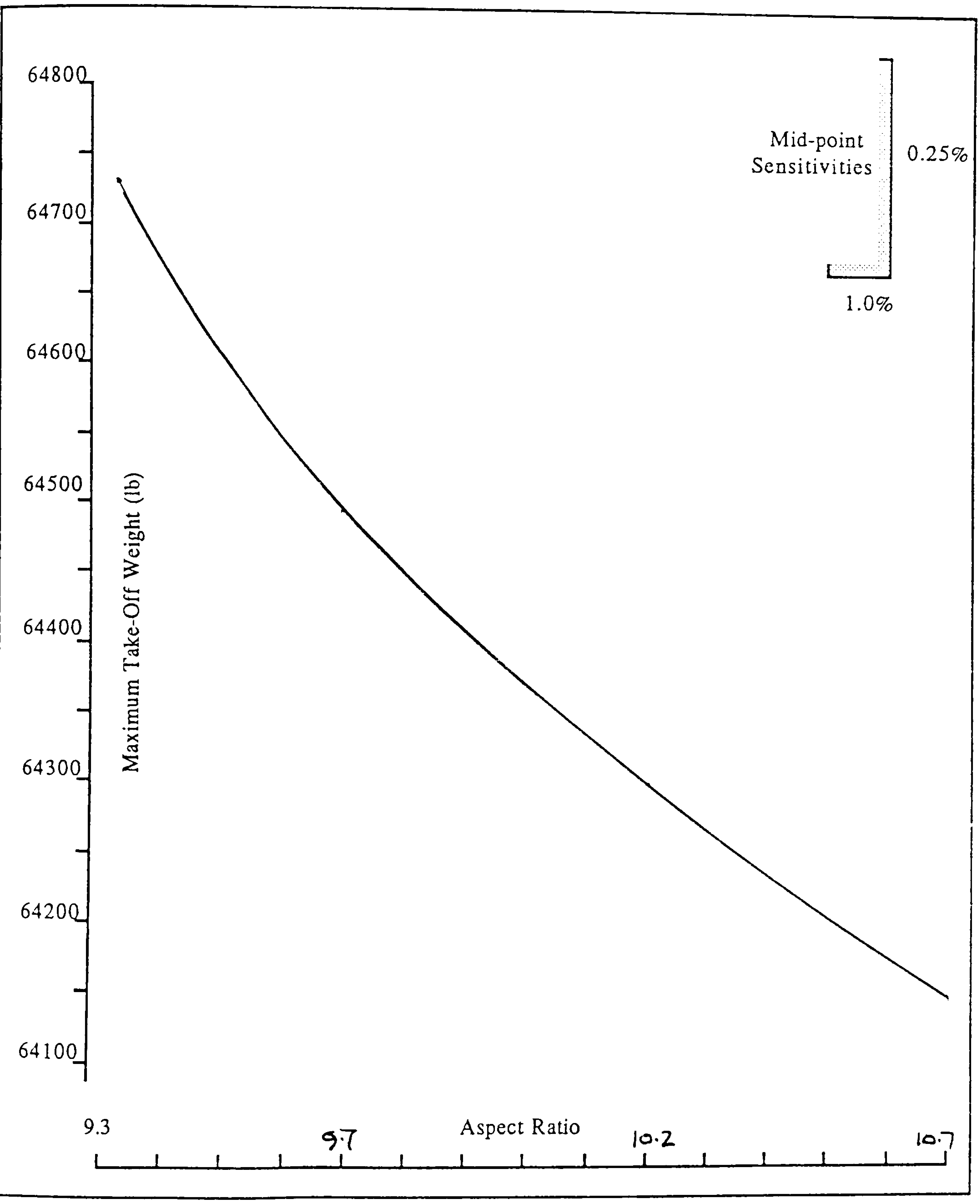


Figure 5.53 Aircraft MTOW. vs. Wing Aspect Ratio

Chapter 6

COMMENTARY

To be of value, research reports must clearly show the strengths and weaknesses of the innovative steps that have been made. This analysis can then be used to highlight the areas where improvements can be introduced into the methodology. This is the format adopted in this chapter which starts with a detailed discussion of the separate parts of the work, continues with a list of the main conclusions and finally makes suggestions for further work which will address some of the weaknesses and limitations that have been observed and extend the work into promising new areas of research.

Before discussing the results from the detail studies it is worth taking a broader view of the use of these methods in the preliminary aircraft design phase. Optimisation methods form only one part of the project design activity and cannot be considered in isolation. The majority of the design effort in the project phase is associated with detail design aspects. The optimisation studies are used to reassure the designers that the detail design decisions are well founded, or to alert them to areas of high sensitivity. The method must be flexible enough to allow different aspects of the design to be investigated quickly. As with all computer methods there is a dilemma to be faced by the designers; the method must be easy to use and not require too much detailed input data, yet over-simplification must not be allowed to disguise the sensitivities. This problem is apparent in the selection of methods to estimate mass, cost and some of the aircraft performance factors (e.g. field lengths). The accuracy of all these methods could be improved by adopting more detailed relationships or estimating methods (e.g. step-by-step analysis of take-off length), but this would involve more information to be provided by the designer and the calculation would take longer. For all the studies the methods developed in this work were regarded as acceptable with regard to input simplification/complexity and calculation speed. The input file details are generated fairly quickly and the optimisation run is completed (on average) in about twenty minutes. Although this run-time cannot be regarded as interactive in the true sense, it is sufficiently fast to allow progressive optimisation studies to be performed and thereby avoid batch error delays.

This 'interactive' feature is seen to be a highly desirable part of the design program. It is often difficult to pre-arrange the study pattern and much time can be saved if changes can be introduced as the early results are digested. Many previous researchers have also observed the requirement for 'interactive-ness' in computer methods used for design. Design programs must have a user interface which allows the designer to interact with the program during the study periods. The PERI-OPT option, which was introduced into the main program at a relatively late stage of development, does not meet this 'designer friendly' criterion and will need to be modified for future work, as described later.

Computer methods are notorious for generating too much output. It is sometimes difficult to disseminate the results of computer work because of the sheer bulk of the output. For program designers it is difficult to anticipate which results are the most significant to the design team and such a selection of results would be bound to change for different types of study. Pre-planning the studies could reduce program flexibility and make it more difficult to use. The optimisation method described here is no exception to this situation. The synthesis program generates a full definition of the optimum aircraft specification and its operational parameters. All this data is useful to the designer and it would be wasteful not to retain all the output data for later investigation. No satisfactory method was devised to distil the ouput into 'handy' parcels for each type of study. On many occasions abridgment of the results would have been unwise because only by looking into the secondary effects contained in the detailed results could a satisfactory explanation be found for some of the trends. It is the detail interrogation of the full output that provides the designer with the best understanding of all the detailed influences in the design process. For this reason, each of the optimum designs was output in full. To present the results in this thesis and to other industrial collaborators, a selection of the results is tabulated. All the full output files are still retained for future reference.

6.1 Discussion

It is clear from the detailed summaries in the previous chapter that all the objectives of the research, as specified in the first chapter (section 1.5), have been achieved. In reaching this situation not only have the benefits of such methods for preliminary aircraft design been demonstrated, but also several drawbacks have been observed. It is proposed to discuss both aspects within each of the study areas which formed the main body of the report.

6.1.1 *LITERATURE SEARCH*

Although this part of the work represents only a supporting aspect of the main study the experiences gained are worth reporting. The use of two different methods of search allowed a comparision to be made between modern and traditional techniques. It was disappointing to discover that the computer search did not provide a complete list of references in the field. The reasons for the deficiencies can only be speculated but the main cause must centre on the way in which the various publications use 'keywords' and 'control terms'. This problem highlights the central dilemma faced by library system managers. If too many keywords are available, the categorisation becomes too fragmented and there is a high possibility that similar types of publication will not be coded alike. On the other hand, if too few keywords are offered it becomes difficult to reduce the list of entries to a manageable number. At the present state of system development there is little guidance offered on the selection of control word structure yet the NASA datafile comprises two large thesaurus-type volumes of keywords. For such reasons the new systems can only currently be used as a complementary search method to the traditional approach. They do however offer the prospect of quick information retrieval that can back-up other methods effectively.

The literature review revealed considerable interest in the subject of aircraft design and optimisation, but not many of the references were also associated with commuter (or short-haul) aircraft. In one respect this was reassuring since it confirmed the novelty of the current work. On the other hand the shortage of references may have been due to the lack of interest in the field. This was discounted when the market for commuter aircraft was analysed (see below). The influence of computers is clearly demonstrated in the listings. Most of the later publications are associated with computer methods and the latest conference proceedings confirm this trend to be continuing.

Dr. Kuchemann's comments on aircraft design methods (reproduced in chapter 2) are seen as particularly far-sighted and serve to justify the current work.

6.1.2 *COMMUTER OPERATIONS & AIRCRAFT*

Analysis of the commuter market was both encouraging and disappointing. The market projection made by several independent bodies showed the expectation of a buoyant demand for commuter air travel over the next decade and beyond. The theoretical description of the short-haul transport gap (Bouladon) still holds good and no mode of travel has managed to make significant gains in this area over the past twenty years. Commuter air services could partly fill this gap if attention was also given to the non-design aspects raised by the STAT report. All market surveys for regional air transport show significant increases over the next decade and this must translate into a strong demand for aircraft. This success will bring with it some attendant problems. Most notable of these problems will be those associated with congestion and environmental impact at the regional airport. Both these will influence the market by encouraging the introduction of larger capacity aircraft. To maintain an acceptable frequency of service and to respond to customer/market demand, these aircraft will need to operate at faster block speeds. Such trends have been observed in the analysis of aircraft types (chapter 3) and correspond to the renewed interest in turbo-fan commuter aircraft.

The US sector has historically dominated the regional market. It still accounts for about 80% of all traffic and will continue to be the leading sector for many years. There are now encouraging signs that the European sector will develop more rapidly in the future. The establishment of the Single European Act in 1992, the liberalisation of the eastern European countries, the increase in regional businesses and the general increase in affluence, all offer considerable confidence for the rapid development of European regional air services. Traditionally the European aircraft manufacturers have been the most successful at supplying the commuter market and this provides further evidence in support for an optimistic future in the industry.

The disappointment mentioned above arose mainly from the analysis of current and projected commuter-type aircraft. No useful project design data could be identified from this analysis. In order to compile a statistically significant sample of aircraft, the operational characteristics and size of aircraft considered may have been too broad. This led to an unacceptable variability in the calculated parameter values. Only generalised trends could be recognised. For example, new aircraft projects were seen to have faster cruise speeds and be larger than their predecessors. Such conclusions could have been reached without such detailed statistical analysis.

Investigation of the mass data showed the high zero-fuel mass ratio for this type of aircraft. It is known that in such cases the aircraft design is much more sensitive to mass changes due to the exaggerated influences on aircraft operating charateristics, particularly range. This may partly account for some of the variability found in the 'real' aircraft data. Many of these aircraft are developments from previous models, therefore they may have inherent weight/aerodynamic penalties carried over from the older design/manufacturing methods. The influence of mass changes (reduction) has been investigated in the industrial optimisation studies discussed in detail in a later section. These studies confirmed this high sensitivity. Although short-haul (commuter) aircraft designed in the past have often been utilitarian in construction (and sometime in design), it is clear from these observations that the introduction of advanced technology features (materials and systems) would have a high return for such types. Also the use of initial project design methods which direct the configuration towards the optimum area is seen to be highly beneficial. The efficiency of the design must be kept high for commuter aircraft to be competitive.

The projections made by Legg from the Shorts market survey, and used as a basis for some of the optimisation studies, are seen to be in the data area of the aircraft survey. With no better relationships available to link aircraft size with range and field performance, the Legg values are accepted as the basis for the industrial studies.

6.1.3 *SYNTHESIS MODEL*

During the development and use of the model, several points were raised which are worth discussing as they may influence future work in this area.

The choice of estimating relationships represents a difficulty to the program designer. Methods tuned to a particular manufacturer or type may not be appropriate to a different scenario whereas generalised methods may not give sufficient weighting to significant features of the design. Such choices were faced in the specification of the aircraft operating cost module. Although generalised methods have been proposed for DOC estimation in the past, such methods are now not considered accurate enough, especially for commuter operations. Each manufacturer and airline has a different philosphy for such estimations. For example, in the current model both 'interest on capital employed' and 'landing fees' are considered as too variable to be accurately predicted; they are both set to zero. With such variability apparent in the estimating methods, it is essential that flexibility is built into the program even if this means a substantial increase in the number of input values. In this program the cost model increases the number of inputs by about 40% but most of these values are held constant throughout a series of optimisations. This aspect presents a good example of the influence of model flexibility on input file size as discussed below.

Estimating equations

All the equations that are used in the synthesis program are fully described in chapter 4 and appendix C. For optimisation methods these equations must accurately reflect the variability of all the design parameters. This requirement dictates the choice of estimating equations and methods. In some cases no suitable equations are available and this forces other methods to be used. For example, none of the available equations for the estimation of fuselage mass contained an adequate selection of design variables. To overcome this deficiency several different estimating methods were incorporated into the mass model and an average of the predicted values was used. This technique must be carefully tested before inclusions in the program to avoid errors which may result from the exaggerated influence of some design variables.

In general, the aircraft design equations used in the synthesis model were seen to provide a good estimate for commuter aircraft mass, aerodynamic performance and cost values. The model was compared to more detailed point estimates done by the Shorts design team and found to provide acceptably accurate predictions.

Input file

As mentioned above the definition of input values may present the program designers with a difficult decision area. If too many values are required, the input file becomes complex and apart from the time needed to compile the list there is a higher possibility of errors. If too few values are specified, the program loses flexibility and the sensitivity of the optimiser could be impaired. The input file described in chapter 4 consists of about 70 values plus a further 30 cost coefficients. Many of the input values may remain constant throughout a particular series of optimisations, making control of the file easier but care has to be exercised to ensure that all the necessary variations are included. For example, increasing the number of passengers must be accompanied with an increase in the cabin length. Obtaining the correct balance in the extent and detail of the input file represents a significant part of the development of a successful design program. The present file is considered as providing the correct balance for this type (commuter) of aircraft.

Engine data

The major problem encountered when developing the model concerned manipulation of the engine data. To maximise efficiency and operating life, modern engines use sophisticated engine management systems to control engine performance. This has the effect of introducing discontinuities in the functions representing engine performance. As described in chapter 4, this type of discontinuity does not suit the optimiser. It was necessary to introduce artificial weighting methods to overcome this problem for the new Rolls Royce engine data. These techniques reduce the accuracy of the engine data prediction but do allow smooth operation of the optimiser. The emergence of this problem highlights the need to carefully select the equations and methods used in the synthesis module to avoid discontinuities. The 'blend' function developed by Collingbourne and Edwards at RAE has been successfully employed in the program to overcome potential problems from simple step functions. A more sophisticated blend routine should be developed for use with modern engine data.

6.1.4 *DESIGN STUDIES*

It is always difficult to judge the absolute benefit from particular studies immediately after their completion since some of the effects may be concerned with future developments. This is the case with the industrially related studies performed in conjunction with the FJX project. The initial series of optimisations were used to determine the best specification for the baseline aircraft. The recommendations that were made from this work were of direct value to the designers and the usefulness of the method was immediately demonstrated. The results from the studies relating to aircraft stretch cannot be judged as clearly since the aircraft design has been shelved. The need to consider future design strategy has therefore disappeared. Nevertheless, prior to the demise of the FJX project, it was clear that the influence of aircraft size on all the economic parameters was strong. The optimisation studies provided a convincing argument for rapid development of the aircraft from 44 seat to about 60. The value of such studies in the development of future design strategies lies in the ability to quickly provide detail results to various design options, all based on the same design philosophy.

The detail design recommendations and conclusions arising from the optimisation studies are given in the summary sections of chapter five. From these it is clear that the methodology used in this work produced many useful results. Some general observations from each of the study areas are presented below.

Baseline specification

In order to reduce the size of the total design task down to manageable proportions with the project staff available, the designer is forced to make particular choices for parts of the initial aircraft specification. Selection of the mission profile is such a case. For commuter aircraft it is known that the operator will fly a series of short stage routes (multi-staging). The choice of number of stages and stage distances is infinite, but a careful selection must be made if the aircraft is to be commercially attractive to enough airlines. Without better information, and in order to reduce the demand on the performance estimations, the Shorts designers chose a single stage (1000 nm) mission for all the initial studies. This choice represented an area of doubt in the design specification and the optimisation method was used to test the validity of this mission choice. The optimisation method allows multi-stage missions to be analysed. The choice of equivalent multi-stage missions to the baseline single-stage is difficult to make. Although the optimisation results provided some useful comparisons, they did not give a satisfactory answer to the designers. The weakness in the results arose due to the different operational conditions applying to each mission. For short stage flights the optimiser attempts to fly saw-tooth (climb/descent profiles). The longer range single-stage profile has a high altitude cruise segment of significant length. The trade-off between range and multi-staging could not be accurately deduced from the study. Due to this lack of precision, and the need to compare the optimisation study results with those of the Shorts team, it was decided to ignore multi-staging in all subsequent work. Nevertheless, this situation is unsatisfactory and should be corrected by future investigations. The methods presented here could be developed to analyse the influence of multi-staging and this would form a suitable topic for future work.

Baseline layout

The early work, concerned with the baseline definition, produced the direct trade-off between aircraft geometry changes and aircraft parameters. It would have been difficult (perhaps impossible) to produce such information by traditional project design methods. The curves showing the sensitivity of the design to wing geometry changes (taper, thickness and aspect ratios) are unique. They are based on sets of individually optimised designs and give the total effect on the overall design. Each study point represents a search of between 5000 and 20000 aircraft configurations. The traditional way of producing such geometrical trade-offs would involve a parametric study in which one (or perhaps two) parameters are allowed to vary while keeping all other design variables at their baseline values. This has the effect of cushioning the sensitivity and disguising the absolute benefit or penalty. The avoidance of this effect provides one of the main advantages for the methodology presented here.

The optimisation method was used to show the effect of engine position on the aircraft layout. The results provided a convincing case for wing mounted engines. Many other studies and some previous experience support this conclusion. However, the absolute values determined by the method may be suspect since they were calculated by very crude modifictions to the synthesis model. For example, overall penalties were imposed for undercarriage, fuselage and wing weight effects but little account was taken of aerodynamic changes (e.g. pylonless-wing). The relatively simple estimating methods used for the optimisation method cannot be expected to predict the subtle changes of configuration with sufficient accuracy. This raises a principal difficulty related to the accuracy requirement of the current optimisation methods. This is discussed in more detail later in this chapter.

The optimisation studies concerned with the baseline specification identified the slight over-winging of the proposed FJX layout. The designers were thought to be using this extra wing as an insurance against future weight and drag growth (a design philosphy borne out of many years experience in aircraft project design). The studies indicated the penalties that such a strategy entailed. As the design specification evolved, the designers' foresight was seen to be wise. The original design was slightly stretched and the engine and aircraft operational item masses were increased. This was accommodated without major changes to the wing geometry which by this time had involved many hundreds of man hours spent on technical analysis. In anticipation of further changes, a series of optimisations was conducted which showed the relationship between wing area and engine thrust for various aircraft stretches. This work provided the aircraft designers with the thrust requirement for either no change to the current wing size or for a slight growth (tip and trailing edge extensions). Knowing the projected cost increase for the wing modifications allowed a perceived value to be set for engine improvement. Such trade-off studies are extremely valuable to the designers as the engine manufacturers are always in a highly competitive market and a knowledge of the engine value (to the aircraft company) is useful in assessing different engine options. Correspondingly, the same methods could be used by engine manufacturers to determine the value of engine improvement to particular aircraft models.

The initial aircraft stretch studies provided a useful framework on which the designers could plan the immediate revision to the baseline layout. It also showed the restrictive influence exerted by the original CFE engine and provided the motivation to seek alternative powerplants. In both these cases the detailed investigations are shown to be valuable in the broader strategic planning phase. It is this interrelationship between detail and broad views, and current and future designer policies, which the optimiser is seen to provide the most useful contribution to the project design effort.

Design criterion

It is always difficult to choose the best criterion on which to base the overall design. In fact, due to the variable nature of the airline business, it may be impossible to select one function to suit all customers. The traditional minimum mass criterion used in the past is now considered as too simplistic. The 'total cost' criterion (or at least approximation to such a concept) is now demanded by project managers. Direct operating cost per flight had been used for all previous optimisations, but reassurance was necessary to remove doubts that the choice of optimising criterion was too influential in the design process. The objective function study provided confidence in the choice of criterion and in the methodology. Each of the optimising criteria selected a slightly different aircraft configuration. In all cases the optimum design showed improvement in the value of the function relative to the other studies. Substantial variation in the objective function values were shown (up to +28%). These effects matched expected trends (i.e. minimum DOC required reduced block times and minimum fuel demanded slower cruise speed). When analysing the effects on choice of aircraft configuration it was seen that the selection of optimising criterion had only small influences. The study confirmed the original decision to use DOC/flight and provided evidence that the optimisation process was working correctly.

Competitor aircraft

Some of the ways in which the method was shown to be useful were unexpected. This was so in the study of the Canadair Regional Jet (RJ) aircraft. Assessment of competitor aircraft by the method was not anticipated, but the results provide a relatively unbiased comparison between this and the FJX design. Some of the observations could have been guessed from the known over-powered layout of the RJ. The competitive threat was made clear by the analysis of DOC. Although the RJ was 20% larger (48 seats) than the current FJX design, the operating cost (SMC) is seen to be similar. This information confirmed the advantage of aircraft stretch and reinforced an immediate increase from 40 to 44 (and later 48) seats. The use of the optimisation method to assess the relative strength of different designs is seen as a useful facility.

Aircraft development

The second and third phases of the industrial related studies, in which engine and aircraft stretch were investigated, provided examples of the most effective use of the optimisation methods in the development programme. Prior to these phases the baseline specification had been transformed into an actual aircraft design, and many of the parameter values that were previously free had been decided. The initial optimisation studies had been influential in:-

increasing the wing aspect ratio,
confirming the wing mounted engine position,
confirmed the advantage of quantified overwinging,
shown the limitations of the current engine thrust,
identified the advantages of aircraft stretch to 44 or 48 seats.

The later aircraft development studies provided the necessary minimum changes from these values to match various aircraft and engine developments. Without such studies it would have been impossible to show the relationship between engine and aircraft changes. The advantages arising from over-winging and overpowering the initial design were reaffirmed. The compromises introduced to the early aircraft design, from the extra wing area, were shown to be acceptable because future stretch programmes were made easier to implement. A further set of optimisations showed the effect of using double-slotted flaps in place of the simpler type used on the baseline design. Such a change was shown to be useful only in those cases where extra power was available.

These studies reinforced the view that optimum designs are not necessarily the best choice for aircraft configuration, but a knowledge of the optimum design provides valuable information for use in strategic planning.

The aircraft stretch studies coincided with the restricted launch of the new Rolls Royce engine. It was shown to be possible to crudely model the new engine and perform a set of optimisations. The results when compared with the earlier set using the CFE engine, provided a direct comparison from which the merits of each engine could be judged. The use of the optimiser in this way (to show the influence of major changes to the specification) is seen as a powerful argument for the use of such methods. It would be difficult to achieve an unbiased comparision of this type by traditional methods because the time taken to develop each design in an active development phase may overlap significant changes to the design from other effects.

The engine comparison also provided the aircraft designers with the value of engine improvements. Such information is valuable when negotiating with engine manufacturers for future engine developments.

The later stretch studies, in which the aircraft development programme was integrated with engine developments, provided the aircraft designer with the value of future engine changes relative to the alternative aircraft development. Both types of study give the aircraft manufacturers valuable commercial information which must be useful in contractual negotiations. Perhaps the engine manufacturers should also develop these techniques to balance the information on perceived values.

Generalised designs

The previous studies had all been associated with the FJX development programme. The next series of optimisations showed how the methodology could be used independently of a particular aircraft project. These generalised studies produced carpet plots which are valuable as they allow aircraft of any size (between 60 and 80 seats) to be projected. Engine size, wing area, aircraft mass and operating cost parameters are displayed against aircraft size and mission specifications. The allows the sensitivites of all these parameters to be understood.

Although this series of optimisations was conducted towards the end of the work on commuter aircraft, this type of study is most useful in the preliminary design phase when aircraft and engine sizes have not been fixed.

It is at this stage that generalised design methods can be extremely valuable to the designers. Such studies provide a framework on which to judge the relative performance of various designs and thereby the starting point for the aircraft specification. Unfortunately, the detail data required to provide a high confidence in such studies is often not available at the beginning of the project design phase.

An extension of this type of study (e.g. 80 seat designs) allowed the designers a closer insight into the choice of stage and field performance. For example, the reducing return on seat mile cost for stage distances greater than 1300 sm, and the continuously strong influence from the field specification, are features that would have been difficult to show by other types of analysis.

An interesting feature was highlighted by the generalised studies. The sensitivity of the field length specification was shown to be low when considering engine size, aircraft MTOW and aircraft DOC per flight, but high when looking at wing area and seat mile costs. This phenomenon presents a challenge to the established project design methods which traditionally have been over-dependent on a minimum aircraft weight design philosophy and as such may have underestimated the influence of field length on aircraft seat mile costs.

The accuracy of all the curves is dependent on the aircraft design model used (see later comments). In this case, the model was validated against the 44 seat FJX aircraft. This was the only design available with design data in sufficient detail to assess the accuracy of the model. It remains uncertain that the model can be extrapolated up to 80 seats and maintain reasonable accuracy, but the results appear to be sensible.

Mass sensitivity
The survey of existing aircraft indicated the high zero-fuel mass fraction for this type of aircraft, and thereby the possible increased influence of weight control in the design. The mass sensitivity studies confirmed this observation. Mass changes are shown to be highly influential to aircraft performance, making sustantial changes to range and field distances. All aircraft designs could be lighter but at a 'cost' (e.g. increased price, complexity and maintenance). This type of study provides the designer with a means of assessing the 'value' of weight reduction at the project stage. For new commuter aircraft the high rate of return for weight saving would suggest the advantage of introducing modern materials and systems into the initial design. The traditional view of short-haul aircraft being "utilitarian" is seen to be technically unsound. These aircraft would benefit more than most types by the introduction of advanced technology.

6.1.5 OVERALL ASSESSMENT OF THE METHOD

In all the optimisation studies, the design model was seen to be well-behaved and the resulting design surface was relatively smooth. Repeated searches from different starting values showed the 'evenness' of the surface, without local depressions. The optimum designs were seen to frequently reside at the intersection of constraint boundaries. As the type of problem was generalised, the optimiser was shown to select a design strategy similar to the traditional project method. Recognising this similarity increased confidence in the optimisation methodology. Some further thoughts on efficiency and accuracy of the optimiser follow.

Optimiser efficiency
Optimisation methods of the type used in the RAE program can be criticised for inefficiency. Although there is little doubt that the mathematical methods used in the search routines are well designed, and use the best methods

available, they still involve considerable internal manipulation of data to determine the derivatives of the design surface functions at each point considered. It has been estimated that approximately half of the total calculation time for a particular study is used for such internal processing. The remaining time is used for repeated passes through the synthesis module. At each pass a complete aircraft is analysed (mass, balance, drag, lift, performance, cost). Typically between 5000 and 20000 such aircraft are analysed for each optimisation run. At the end of the process only the final (optimum) aircraft design is made available. This process also represents a considerable amount of computational effort which is discarded. For both these reasons the effectivness of the computational effort must be challenged.

As computer technology improves, the need for sophisticated search methods may be reduced. Optimisation methods may be based on fast repetitive processes with a simple, perhaps even random, strategy for selecting the design points. The best series of designs could then be offered to the designers for further consideration. With such a process the synthesis model would not need to be compromised (as at present), by the optimisation search methods. Discontinuities and constraint boundaries should not present any problem to such methods. Further work concerning in-depth investigation of alternative "optimisation methods" should be started as soon as possible.

Optimisation accuracy

Accuracy of the synthesis model is a continuous cause for concern. The optimisation method demands a much finer tolerance than the estimating equations can guarantee. This means that the influences from the individual aircraft parameters may be incorrectly represented. Design equations used in the synthesis model have been taken from previous project methods. These relationships have been developed to provide reasonably accurate predictions of the gross effect on the overall design of the aircraft and have not been too concerned with individual components. This aspect has been demonstrated in the analysis of mass prediction methods. Some of the statisically best relationships, from an overall viewpoint, have been those with fewest aircraft variables.

This situation is further complicated by the need to accurately represent all the design variables in the equations and for such relationship to be quickly evaluated. The balance to be drawn between analysis methods which reflect the variability of the parameters with sufficient accuracy and the simplification of the relationships to permit rapid evaluation, represents a major difficulty in the developments of optimisation methods. For the model described here the selection of appropriate methods benefited from the work done earlier on turbo-prop. designs and the close industrial collaboration that existed.

6.1.6 *PERI-OPT FACILITY*

This facility provided an innovative development in the output of results. The PERI-OPT graphs did clearly show the shape of the design surface (or an approximation to it) around the optimum design, with respect to the chosen design variables. They also showed the position and shape of the main constraint boundaries. The relative smoothness of the design surface contours and the influence of the constraint boundary intersection, confirmed the observations from the textural output. It was felt that such a facility was useful in providing an understanding of the design surface and the influence of the constraints. The existing PERI-OPT program is rather clumsy to use and does not contain an editing facility. The method requires a complete redesign of the user-interface to overcome these problems. Extra work on the PERI-OPT facility would be worth pursuing, particularly for 'academic' use of the optimisation method.

6.1.7 *NEW STUDIES*

The studies described above are regarded as forming a comprehensive set covering all the significant design areas. Apart from small improvements to the estimating model, the only new work (studies) envisaged is concerned with the following topics:-

Part-load factors

It is recognised that passenger/freight load factors for commuter aircraft average 60 to 70%. All the previous studies have assumed a full passenger load. With a slight alteration to the program structure it should be possible to design aircraft on the basis of partial load factors.

Extended range aircraft

The traditional design point (top right-hand corner of the payload/range diagram) has been used in all the previous studies. The effect of linking extended range with reduced passenger load could be investigated, to identify the sensitivity of various design parameters.

Advanced technologies

The existing program includes several factors (XX...) in the input file specification, to allow changes to the existing routines. These factors could be used to simulate changes in technology. It may be necessary to introduce extra factors into the cost model to account for corresponding changes in system, airframe and material prices and to anticipate the effects of such technology changes on maintenance costs.

Each of the topics above was considered as lying outside the scope of the current work.

6.2 Conclusions

The following lists itemise the main conclusions drawn from the preceding work. Three separate, but in some aspects highly inter-related lists are presented.

6.2.1 AIRCRAFT DESIGN

The detailed technical conclusions from each study can be found in the summary sections within chapter 5, they have not been repeated here.

1. The model used for the baseline aircraft stretch studies provided a useful framework of results on which the designers could plan immediate revision to the baseline aircraft.

2. For the baseline layout study, the method was confirmed by the results from traditional calculations. Doubt is raised with regard to the accuracy of some of the estimating relationships used to model major configurational changes (e.g., the effect of rear engine position.)

3. The optimisation model correctly selected designs for different objective functions. The selection of objective function was shown to have only small influence on the optimum aircraft geometry. The study confirmed the decision to use DOC per flight as the principal optimisation function.

4. The high zero-fuel mass ratio of commuter aircraft signals a high susceptibility to mass changes. This was confirmed by a detailed optimisation study. These aircraft will therefore benefit from the use of efficient project design methods and the adoption of advance technologies.

5. The optimisation method can be used to provide a 'value' for aircraft thrust increase based on the total effect on the aircraft design.

6. The use of the optimisation method to show the wing geometry trade-offs on the baseline design was seen to be an improvement over traditional parametric studies.

7. For commuter aircraft of the type investigated there are advantages to over-winging and over-powering the initial design. This strategy allows initial stretch programmes to be more easily implemented. This reinforces the conclusion that optimum designs are not necessarily the best choice for the initial aircraft configuration.

8. The investigation into the effect of multi-staging was seen to be inconclusive. More work is needed to fully understand the implications of various missions on aircraft design.

9. Aircraft and engine stretch studies provide the most effective use of the optimisation method. They allow the sensitivity of all the aircraft parameters to be displayed against aircraft size and missions specifications. Such information is valuable in the definition of future aircraft development strategies.

10. The optimisation method was found to be useful in assessing competitor aircraft, and provided a standard method of analysis for judging the relative strength of new versus established designs.

6.2.2 OPTIMISATION METHOD

1. The computer program was well-behaved and shown to be easily transferred to different computer systems.

2. The optimisation method was shown to give consistent and accurate results in all types of study. It provided a better understanding of the design surface and the influence of the design constraints than traditional methods.

3. The operational requirements of the optimiser is seen to be at variance with traditional aircraft project design methods. The level of detail, and accuracy, demanded by the optimiser is higher than traditional methods provide. The use of such methods for optimisation work may give misleading results if careful validation of the model is not performed.

4. The optimising method is regarded as wasteful in aircraft design effort since only the final result (optimum) is output. The internal search routines are also seen to be time consuming. Both these features may be improved by the development of new computer technology and methods.

5. The PERI-OPT graphical presentation of the design surface and constraint boundaries was regarded as a useful facility. Improvements in the user interface are necessary. Use of the method for undergraduate teaching purposes should be investigated.

6.2.3 MISCELLANEOUS TOPICS

1. Due to variability in the data available from published sources, it was difficult to deduce useful design trends and detailed parameter relationships for commuter aircraft from an analysis of 'actual' aircraft data conducted in this research. A more detailed and consistant set of data would be necessary before sufficient confidence could be assigned to such analysis for use in aircraft design synthesis.

2. The literature review showed a continuing interest in the field of aircraft project design, computer-aided methods and optimisation methods, but little application to commuter-type design.

3. Computer-based literature search methods were found to omit some of the most significant publications. This may be attributed to assignment of keywords. At this stage in their development, such methods should only be used as a support to the traditional forms of literature search.

6.3 Recommendations for future work

Research is a continually developing process. To assist future workers in the field the following recommendations are made for new work:-

1. The synthesis model should be improved with regard to the wing stiffness criterion, compressibility effects and to model the influences of rear engine layout more accurately.

2. The synthesis model should be improved to more accurately simulate the Rolls Royce engine and thereby account for modern engine management systems. This may involve the development of a more sophisticated BLEND subroutine.

3. The cost routines should be generalised to account for cost relationships

different to the Shorts' methods.

4. The program file structure should be modified to allow direct comparison to earlier optimisation runs.

5. The optimiser should be used to study the effect of multi-staging on optimum aircraft design.

6. The method should be used to study the effects of partial passenger load factor, extended range, and the introduction of advanced technology on optimum aircraft design.

7. Investigations should be made into alternative optimisation methods and the new methods compared to the gradient search techniques used by the RAE program.

8. A detailed analysis of the synthesis model and optimiser accuracy requirements should be made.

9. The PERI-OPT facility should be redesigned to improve the user interface.

10. The improved PERI-OPT and optimisation program should be used to investigate the suitability for undergraduate teaching of aircraft project design.

FOOTNOTE

I hope that by following the suggestions for new work listed above, future researchers will find as much personal satisfaction and professional fulfilment as I have in completing the work to this stage.

Finally, I would like to thank everyone who has read through the thesis and hope the fascination that is such an essential feature when projecting new aircraft designs has shone through the minutiae that was necessary to make the thesis a complete record of my work.

APPENDIX A

Quest Library Searches using ESA/IRS-NASA database : August 1989

SEARCH 1 : Aircraft Design/Optimisation/(Short Haul Aircraft or Commuter Aircraft or Passenger Aircraft) Number of references = 39

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"Weight design and efficiency of passenger aircraft"

9. *Edlund & Nilsson*, Saab-Scania AB, Sweden. September 1984
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"Aircraft design"

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12. *Aronson*, Aronson Industries, Orlando. U.S.A. January 1982
"Optimum configuration for a 10 passenger business turbofan jet airplane"

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"Aircraft evaluation in air network planning"

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17. *Hujecek*, Zpravodoj VZLU. 1981 (In Czech)
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18. *Saulas*, Avions Marcel Dassault-Brequet Aviation. November 1980
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25. *Wedderspoon*. British Arospace, Weybridge. June 1978.
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"The air traffic of the 1980's and its aircraft and fleet structure requirements"

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"Resolving the contradictions between airplane component weight and drag"

34. *Schneider, Mader* SAWE Conference, U.S.A. May 1974.
"Weight control and how we look at it (in aircraft design and production)"

35. *Gogolin*. Aviatsionnaia Tekhnika. 1974 (In Russian).
"Resolution of a conflict between weight and component drag in an aircraft"

36. *Kirkpatrick & Peckham.* Royal Aircraft Establishment. Bedford. October 1972.
"Multivariate analysis applied to aircraft optimisation - some effects of research advances on the design of future subsonic transport aircraft".

37. *Chopping.* Intervia. February 1972.
"Another thoroughbred from Dassault - Falcon 10 flight report. (Dassault Flacon 10 turbofan powered executive aircraft, attributing safe stall characteristics to wing design optimization).

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39. *Och.* Messerschmitt-Boelkow-Blohm GMBH, Munich. March 1969.
"Use of fibreglass-reinforced plastic for bearing components in light aircraft construction (All-plastic light passenger aircraft with inflated tube construction for shell, design and performance)"

SEARCH 2 : Airline Operations/(Short Haul Aircraft or Commuter Aircraft)
Total Number of references = 147, Selected references = 57 shown below

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5. *Roskam, Wyatt, Griswold & Hammer.* Kansas University. 1977
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7. *Turk & Zeiner.* Garrett Turbine Engine Co. Phoenix. June 1986-
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8. *Kaehler & Schneider.* Avco Lycoming Textron. U.S.A. June 1986
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9. *Cooper & McKenna.* California Polytechnic State University. January 1986.
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APPENDIX B

This appendix contains the tabulated results from the survey of aircraft (chapter 3).
There are four sets of data :-

B1 Data on old aircraft types
B2 Data oin current aircraft
B3 Data on new and projected aircraft
B4 Derived data on current aircraft

In each figure (sheet 1) provides data in SI units, and (sheet 2) in Imperial units.

Aircraft Type	Seats	MTOW	OEW	Area	Span	V Cruise	Range	TO Dist.	Land Dis	Price
		Kg.	Kg.	Sq.m.	metres	m/sec	Km.	metres	metres	$M 1987
Shorts SD7	19	5669	3306	34.65	19.78	142.6	567	485	434	
DHC 6-300	20	5669	3363	39.02	19.81	97.8	1074	402	320	
Beech 99	15	5125	2946	25.92	13.96	128.2	1685	617	753	
Let 410	15	5799	3800	35.18	19.45	101.4	1039	520	810	
Embraer-110	21	5669	3515	29.10	15.33	114.8	2000	675	698	
Shorts SD330	30	10385	6679	42.08	22.77	97.8	1694	1158	1143	
VFW 614	40	17247	10998	63.92	21.55	177.1	759	1150	1090	
Fokker F28	65	25714	15007	76.37	23.56	204.4	1180	1219	1280	
DHC Dash7	50	19955	12558	79.90	28.35	118.9	1278	1829	823	
B737-100	101	48526	25428	91.04	28.35	257.4	2748	2073	1500	
DC9-30	100	44444	24009	86.80	28.47	295.0	3852	2484	1463	
BAC 1-11	109	44444	24748	93.18	28.50	257.4	1215	1829	1800	

Figure B1 (Sheet 1)   Technical Data for Old Aircraft (SI Units)

Aircraft Type	Seats	MTOW	OEW	Area	Span	V Cruise	Range	TO Dist.	Land Dis	Price
		lb.	lb.	Sq.ft.	Feet	Knots	N.miles	Feet	Feet	$M 1987
Shorts SD7	19	12500	7289	373	64.9	277	306	1590	1425	
DHC 6-300	20	12500	7415	420	65.0	190	920	1320	1050	
Beech 99	15	11300	6495	279	45.8	249	910	2025	2470	
Let 410	15	12786	8378	379	63.8	197	561	1706	2657	
Embraer-110	21	12500	7751	313	50.3	223	1080	2215	2290	
Shorts SD330	30	22900	14727	453	74.7	190	915	3800	3750	
VFW 614	40	38030	24251	688	70.7	344	410	3775	3576	
Fokker F28	65	56700	33090	822	77.3	397	637	4000	4200	
DHC Dash7	50	44000	27690	860	93.0	231	690	6000	2700	
B737-100	101	107000	56069	980	93.0	500	1484	6800	4920	
DC9-30	100	98000	52935	934	93.4	573	2080	8150	4800	
BAC 1-11	109	98000	54570	1003	93.5	500	656	6000	5900	

Figure B1 (Sheet 2) Technical Data for Old Aircraft (Imperial Units)

Aircraft Type	Seats	MTOW	OEW	Area	Span	V Cruise	Range	TO Dist.	Land Dis	Price
		Kg.	Kg.	Sq.m.	metres	m/sec	Km.	metres	metres	$M 1987
Jetstream-31	18	6949	4340	25.2	15.85	135.4	1259	1219	1006	2.8
Doe 228-202	19	6209	3746	32.0	17.00	121.0	5767	650	457	2.7
Beech 1900	19	7528	4308	28.2	16.58	131.8	1819	994	774	3.5
CASA 212	28	7698	4829	41.0	20.27	102.0	626	649	582	
Shorts 360	36	11989	7664	42.2	22.77	109.1	806	1362	1200	4.6
Embraer-120	30	11498	7029	39.4	19.75	154.4	1750	1420	1372	5.3
Dash 8-100	36	15646	9977	54.4	25.91	136.4	2019	960	908	7.0
Dash 8-300	50	18640	11202	56.2	27.43	146.7	1667	1120	1109	9.5
Saab 340	35	12370	7898	41.8	21.43	141.6	1056	1173	1009	6.0
ATR 42	42	16696	9971	54.5	24.57	137.4	2093	1010	960	~7.0
ATR 72	70	19986	11666	61.0	27.00	147.2	1667	1329	1135	~8.6
BAe -ATP	64	22449	13592	78.3	30.68	136.4	1826	1539	1097	10.5
BAe 146-100	82	38095	22222	77.3	26.21	218.8	2370	1219	1106	16.0
Let -610	40	13998	8998	56.0	25.60	135.9	858	613	545	
Fokker 50	50	20816	12834	70.0	29.00	147.7	2524	1698	1081	~9.0
Fokker 100	107	43084	23865	93.5	28.07	222.4	2222	1975	1360	~19.0
CASA 235	45	15098	9399	59.0	25.82	125.6	1239	742	771	

Figure B2 (Sheet 1) Technical Data for Current Aircraft (SI Units)

Aircraft Type	Seats	MTOW	OEW	Area	Span	V Cruise	Range	TO Dist.	Land Dis	Price
		lb.	lb.	Sq.ft.	Feet	Knots	N.miles	Feet	Feet	$M 1987
Jetstream-31	18	15322	9570	271	52.0	263	680	4000	3300	2.8
Doe 228-202	19	13690	8260	344	55.7	235	314	2132	1500	2.7
Beech 1900	19	16600	9500	303	54.4	256	982	3260	2540	3.5
CASA 212	28	16975	10648	441	66.5	198	338	2129	1909	
Shorts 360	36	26435	16900	454	74.7	212	435	4470	3940	4.6
Embraer-120	30	25353	15498	424	64.8	300	945	4660	4500	5.3
Dash 8-100	36	34500	22000	585	85.0	265	1090	3150	2980	7.0
Dash 8-300	50	41100	24700	605	90.0	285	900	3675	3640	9.5
Saab 340	35	27275	17415	450	70.3	275	570	3850	3310	6.0
ATR 42	42	36815	21986	587	80.6	267	1130	3315	3450	~7.0
ATR 72	70	44070	25724	657	88.7	286	900	4363	3723	~8.6
BAe -ATP	64	49500	29970	843	100.5	265	986	5050	3600	10.5
BAe 146-100	82	84000	49000	832	86.0	425	1280	4000	3630	16.0
Let -610	40	30865	19841	603	84.0	264	469	2011	1788	
Fokker 50	50	45900	28300	754	95.1	287	1363	5570	3547	~9.0
Fokker 100	107	95000	52624	1006	92.1	432	1200	6480	4462	~19.0
CASA 235	45	33290	20725	636	84.7	244	669	2400	2530	

Figure B2 (Sheet 2) Technical Data for Current Aircraft (Imperial Units)

Aircraft Type	Seats	MTOW	OEW	Area	Span	V Cruise	Range	TO Dist.	Land Dis	Price
		Kg.	Kg.	Sq.m.	metres	m/sec	Km.	metres	metres	$M 1987
Embraer -123	19	8498	5639	27.21	17.71	180	1111	1040	1090	
Jetstream -41	29	10148	6143	32.52	18.29	149	1093			
Shorts FJX	44	18322	11426	55.00	25.29	216	1802	1640	1305	
Canadair RJ	50	21428	13143	54.00	21.43	236	1689	1585	1631	
Saab -2000	50	20635	12472	55.74	24.00	185	2037	1494	1494	
Dash 8 -400	68	25175	14515	59.30	25.90	180	2222	1220	1340	
Dornier -328	33	12498			20.03	178	1296	1006	1006	
Embraer -145	48	16497	9558	50.00	22.34	208	1204	1494	1372	
MBB/MPC -75	69	32494		75.00	24.69		2778	1585	1250	
Metro V	19	7483		29.50	17.71	148	907	1425	815	

Figure B3 (Sheet 1) Technical Data for Projected Aircraft (SI Units)

Aircraft Type	Seats	MTOW	OEW	Area	Span	V Cruise	Range	TO Dist.	Land Dis	Price
		lb.	lb.	Sq.ft.	Feet	Knots	N.miles	Feet	Feet	$M 1987
Embraer -123	19	18739	12434	292.8	58.1	351	600	3412	3576	
Jetstream -41	29	22377	13545	350.0	60.0	290	590			
Shorts FJX	44	40400	25195	592.0	83.9	420	973	5380	4280	
Canadair RJ	50	47250	28980	581.1	70.3	459	912	5200	5350	
Saab -2000	50	45500	27500	600.0	78.7	360	1100	4900	4900	
Dash 8 -400	68	55500	32000	638.6	85.0	350	1200	4000	4400	
Dornier -328	33	27557			65.7	345	700	3300	3300	
Embraer -145	48	36376	21076	538.2	73.3	405	650	4900	4500	
MBB/MPC -75	69	71650		807.3	81.0		1500	5200	4100	
Metro V	19	16500		317.5	58.1	288	490	4675	2675	

Figure B3 (Sheet 2) Technical Data for Projected Aircraft (Imperial Units)

Aircraft Type	PAX	MTOW	OEW	OEW	Wing	MTO	MTO	PAX.VC	OEW	PAX
		PAX	PAX	MTO	AR	Area	Span	MTOW	$M	$M
Jetstream-31	18	386.1	241.1	62.50	9.97	275.8	438.4	.351	1523	6.32
Doc 228-202	19	326.8	197.2	60.34	9.00	194.0	365.2	.370	1362	6.91
Beech 1900	19	396.2	226.7	57.23	9.78	267.4	454.0	.333	1231	5.43
CASA 212	28	274.9	172.5	62.73	10.02	189.8	379.8	.371		
Shorts 360	36	333.0	212.9	64.02	12.31	284.2	526.5	.328	1666	(7.83)
Embraer-120	30	383.3	234.3	61.13	9.89	291.6	582.2	.403	1323	5.66
Dash 8-100	36	434.6	277.1	63.77	12.35	287.9	603.9	.314	1425	5.14
Dash 8-300	50	372.8	224.0	60.10	13.39	331.6	679.3	.394	1179	5.26
Saab 340	35	353.4	225.7	63.85	10.99	295.8	577.2	.401	1316	5.83
ATR 42	42	397.5	237.4	59.72	11.06	306.3	679.5	.346	1424	6.00
ATR 72	70	285.5	166.7	58.37	12.00	327.6	740.2	.516	1356	(8.09)
BAe -ATP	64	350.8	212.4	60.55	11.98	286.6	732.9	.389	1294	6.09
BAe 146-100	82	464.6	271.0	58.33	8.89	(492.9)	(1453)	.471	1389	5.12
Let -610	40	349.9	224.9	64.28	11.71	250.0	546.8	.388		
Fokker 50	50	416.3	256.7	61.66	12.00	277.4	717.8	.355	1426	5.56
Fokker 100	107	402.7	223.0	55.39	8.43	(460.8)	(1534)	.552	1256	5.63
CASA 235	45	335.5	208.9	62.26	11.28	255.9	584.7	.374		

Figure B4 (Sheet 1) Derived Data for Current Aircraft (SI Units)

Aircraft Type	PAX	MTOW	OEW	OEW	Wing	MTO	MTO	PAX.VC	OEW	PAX
		PAX	PAX	MTO	AR	Area	Span	MTOW	$M	$M
Jetstream-31	18	851	531	62.50	9.97	56.48	294.6	.309	3357	6.32
Doc 228-202	19	720	434	60.34	9.00	39.76	245.9	.326	3003	6.91
Beech 1900	19	873	500	57.23	9.78	54.78	305.1	.293	2714	5.43
CASA 212	28	606	380	62.73	10.02	38.47	255.3	.327		
Shorts 360	36	734	469	64.02	12.31	58.23	353.6	.289	3673	(7.83)
Embraer-120	30	845	516	61.13	9.89	59.74	390.9	.355	2924	5.66
Dash 8-100	36	958	611	63.77	12.35	58.97	405.9	.276	3142	5.14
Dash 8-300	50	822	494	60.10	13.39	67.93	456.7	.347	2600	5.26
Saab 340	35	779	497	63.85	10.99	60.61	387.8	.353	2900	5.83
ATR 42	42	876	523	59.72	11.06	62.76	456.9	.305	3141	6.00
ATR 72	70	629	367	58.37	12.00	67.12	519.1	.454	2973	(8.09)
BAc -ATP	64	773	468	60.55	11.98	58.72	492.0	.343	2854	6.09
BAc 146-100	82	(1024)	597	58.33	8.89	(100.96)	(976.7)	.415	3062	5.12
Let -610	40	771	496	64.28	11.71	51.20	367.4	.342		
Fokker 50	50	918	566	61.66	12.00	60.92	482.7	.313	3144	5.56
Fokker 100	107	887	491	55.39	8.43	(94.40)	(1031.7)	.487	2769	5.63
CASA 235	45	739	460	62.26	11.28	52.33	393.2	.330		

Figure B4 (Sheet 2) Derived Data for Current Aircraft (Imperial Units)

APPENDIX C

This appendix contains a full discription of all the synthesis modules shown in figure 4.6. of chapter 4.

The appendix covers the following modules:-

C1. Input of aircraft data
C2. Geometry calculations
C3. Mass estimation
C4. CG and balance calculations
C5. Aerodynamic analysis
C6. Stability analysis
C7. Engine data interpretation
C8. Performance estimation
C9. Cost estimation
C10. Output of all results

C1 Input Specification

The input data consists of:-

(1) a set of *fixed values* for some of the aircraft geometry features, engine characteristics, aerodynamic aspects, mass estimation coefficients, payload/mission and cost parameters.
(2) the *design variable* list, including the maximum and minimum limits of each value and the optimum search start point values.
(3) the *problem constraint* functions
(4) the *objective function* specification
(5) *optimiser control* values

A detailed description of each input value (in SI units) is given below:-
A specimen of the full input file is shown in Appendix F).

C1.1 *FIXED DATA*

Geometric Data			*Typical Value*
DFUS	=	Fuselage Diameter	2.89
LF1	=	Fuselage length (nose to cabin)	4.00
LF2	=	Cabin Length	15.65
FINCID	=	Fuse/wing setting angle	3.0
IWING	=	Wing position indicator (0 = low, 1 = high)	0
VDIVE	=	Design Max. Speed	205.0

IROWS	=	Number of seats across	4
DNAC	=	Nacelle Diameter	1.00
LNAC	=	Nacelle Length	3.30
LN	=	Distance nacelle L.E. is forward of wing $^{c}/4$ line	2.2
ARH	=	Horizontal tail, Aspect ratio	4.70
TRH	=	Horizontal tail, Taper ratio	0.50
TCH	=	Horizontal tail, Thickness ratio	0.11
VH	=	Horizontal tail, Volume coefficient	1.134
ITAIL	=	Tail position indicator (0 = Low, 1 = Tee)	0
QHQ	=	Tail velocity parameter (unused for jet aircraft)	-
ARV	=	Vertical tail, Aspect ratio	3.00
TRV	=	Vertical tail, Taper ratio	0.50
TCV	=	Vertical tail, Thickness ratio	0.11
VV	=	Vertical tail, Volume coefficient	0.08
VSWEPD	=	Vertical tail, L.E sweep (degrees)	31.39
ENGP	=	Engine position indicator (1 = wing, 0 = rear fuse.)	1
UCP	=	Undercarriage position indicator (1 = wing, 0 = fuselage)	1

Engine Data

ENGL	=	Engine length	2.00
ENGM	=	Engine mass	507.00
ENGLOC	=	Engine spanwise distance (from fuse.CL)	3.81
TOT	=	Take-off engine thrust (lbs)	5770.0
SPEMPG	=	Not used for jet engine analysis	-
IENG	=	" " " "	-
XXSFC	=	Technology improvement factor	1.00
ENGSC	=	Engine scale factor	1.00

Aerodynamic Data

CLA	=	Basic aerofoil lift curve slope	6.10
CLMAX	=	Aerofoil max. lift coefficient	1.70
CLDES	=	Aerofoil design lift coefficient	0.30
CMACW	=	Aerofoil pitching moment coefficient	-0.08
TCRTCW	=	Ratio of root thickness to average	1.10
WSWEPD	=	Wing sweepback angle at $^{c}/4$	21.5
BFOB	=	Flap span ratio to wing span	0.75
CFOC	=	Ratio of flap chord to wing chord	0.30
DFDLAN	=	Landing flap deflection (deg.)	40.0
IFLAP	=	Flap type indicator (1 = single slotted 2 = double slotted, 3 = single slotted with fowler moment, 4 = double slotted fowler)	3
MAXOVO	=	Flap design parameter	1.00

DCLMAX=	Optional max. lift increment due to flaps		0.00
RUFW =	Surface roughness coefficient - wing		1.2
RUFF =	"	- fuselage	1.2
RUFN =	"	- nacelle	1.8

Mass Data

Coefficients to influence mass predictions

XXWIW =	wing	XXENGW = engine	
XXFUW =	fuselage	XXUCW = undercarriage	All
XXTAW =	Tail	XXCONW = controls	set at
XXNAW =	nacelle	XXSYSW = systems	1.0
XXFLAW =	flap	XXFURW = furnishings	

Payload

NPAS =	Number of passengers	40

Mission Requirement

STAGE =	Stage length	various*
INSTAG =	Number of stages	various*
DIVERS =	Diversion distance	185000
HOLDMN =	Hold time (mins)	45
INHSEG =	Number of steps -climb & descent	7
INCSEC =	Number of steps - cruise	5
BFLMAX =	Balanced field length	various*
LFLMAX =	Landing field length	various*
IMLAND =	Landing weight index (1 = max. take-off mass 2 = mass at end of final stage, 3 = mass at end of mission, 4 = mass at end of first stage.)	2
MINMRG =	Minimum static margin	0.05
RODLIM =	Rate of decent limit (for de-pressurisation)	11.953
WATISA =	WAT temperature (above ISA)	20.0
WATH =	WAT height	0.0
GRAMIN =	Second segment climb requirement	0.024
EMBST =	Emergency engine thrust boost	1.07

(* depending on the study pattern)

Cost Coefficients

JSUBC	JOH	JCAM1	
JSRATE	JWRATE	JCAM2	
JFWAST	JWTIME	JCAM3	
JINHO	INUMAC	JCEM1	not used in current version of cost module.
JIRATE	JFPRO	JCEM2	
JUNCA	JDEVC	JCEM3	
JURATE	JCSCI	JCW	
JBOUT	JCSC2	JCLF1	

ENGC	=	Engine price (each) (US $)	950000
JPFUEL	=	Fuel price (US $/litre)	0.02
IENTYP	=	Engine type (1 = CFE , 2 = RB580)	either

C1.2 DESIGN VARIABLES

	Typical Range Min	Max
1. Wing Aspect Ratio (ARW)	7.5	13.5
2. Wing Gross Area (SRFF)	35.0	100.0
3. Wing Taper Ratio (TRW)	0.24	1.00
4. Wing Thickness Ratio (TCW)	0.10	0.15
5. Length Ratio of Rear Fuse.(LF3/DFUS)	2.0	4.0
6. Wing Position Ratio (LFN/LF)	0.1	0.7
7. Take-off flap deflection (DFDTO)	0.0	40.0
8. Dummy variable for Mass Iteration (XMTO)	9000.	35000.
9. Dummy variable for Fuel Mass Inter.(XMFUEL)	100.	10000.
10. Main Mission Climb Speed (VAIAS)	50.	149.
11. Main Mission Cruise Speed (VBIAS)	80.	175.
12. Main Mission Decent Speed (VCIAS)	50.	149.
13. Main Mission Cruise Height (HCRUZ)	5525.	10970.
14. Minimum cruise, first stage segment SB1	0.2	1.0
15. Minimum cruise, notional stage segment SB2	0.2	1.0
16. Minimum cruise diversion stage segment SB3	0.2	1.0
17. Diversion stage cruise speed (VBIAS3)	30.	164.
18. Diversion stage cruise height (HCRUZ3)	1000.	6096.
19. Engine cruise setting (TSET1)	0.5	1.0

C1.3 PROBLEM CONSTRAINTS

1. Static Margin > min.input value	(MINMRG < STATMR)
2. Dummy constraint for mass iteration	(MTOCAL=XMTO)
3. Dummy constraint for fuel iteration	(MFUEL=XMFUEL)
4. Balance Field Length < max input value	(BFL < BFLMAX)
5. Second Seg.Climb Grad. > min.input value	(GRAMIN < WATGRA)
6. Landing Field Length < max. input value	(LFL < LFLMAX)
7. Calculated Stage = input stage	(STAGE=SA1 + SB1 + SC1)
8. Calculated Diversion = input diversion	(DIVERS=SA3 + SB3 + SC3)
9. Cruise Mach No < drag divergent speed	(CRUZMA < 0.85)
10. Descent Time > repressurisation time	(MINTM < TIMC1)
11. Descent Speed < cruise speed	(VCTAS < CRUTAS)

C1.4 OBJECTIVE FUNCTION OPTIONS

1. Minimum Fuel Mass, (MFUCAL)
2. Minimum Aircraft Take-off Mass, (MTOCAL)

3. Minimum DOC per Flight,(DOCPF)
4. Minimum Seat Mile Cost, (SMC)
5. Minimum Wing Mass, (MWING)
6. Min. (Wing + Fuel)+ Mass, (MWING + MFUCAL)

C1.5 OPTIMISER CONTROLS

The optimiser user manual defines several optimiser controls which allows the search to be tuned to the nature of the design surface. All the controls have default values which are adopted if the input file does not specify the parameter. A total of 34 such parameters are described in the user manual of which the following are the most significant:-

RTOL = tolerance on step size for feasibility.
UMAX = largest step size in feasibility routine.
VMAX = largest step size in minimisation routine
OMEGA = reduction factor used in linear searches when given step fails.
XTOLU* = controls the accuracy of the constraint violation.
XTOLV* = controls the accuracy of the objective function minimisation
* the program does not converge unless these tolerances are achieved.

There are two parameters which control the program communication:-

NFEMAX= the maximum number of function evaluations before the program gives up (normally set at 20000).
RFREQ = the frequency of reporting the program's progress to the user terminal (normally set at 100).

C2 Aircraft Geometric Calculations

All the geometric parameters for the aircraft components are evaluated in this section.
The geometry is determined for each of the aircraft major components:-

1. **Wing**
Aspect Ratio: (ARW)
Gross Area: (SREF)
Taper Ratio: (TRW)
Thickness Ratio: (TCW)
} These are design variables

Span: (B) = $(ARW \times SREF)^{0.5}$

Centerline Chord: (CWR) = $\frac{2 \times SREF}{B(1 + TRW)}$

Tip Chord: (CWT) = CWR x TRW

Mean Geometric Chord: (MGC) = $\frac{CWR + CWT}{2}$

Mean Aerodynamic Chord:

(MAC) = $0.667 \times CWR \times \left(\frac{1 + TRW^2}{1 + TRW}\right)$

Root Thickness (TCROOT) = TCRTCW x TCW

(where (TCRTCW) is fixed input data)

Exposed wing span (BX) = B - DFUS

Exposed wing area (SWX) = SREF - (CWR x DFUS)

(where DFUS is fixed input data)

Exposed wing aspect ratio (ARWX) = $\frac{BX^2}{SWX}$

Wing position factors

a) Fuse. Nose to Wing root (c/4)

(LFQC) = LFN + 0.25 CWR (where LFN is a design variable)

b) Fuse. Nose to Wing c.p.

(LFAC) = LFQC + $\frac{B}{4}$ tan (WSWEEP)

(where wing sweepback is an input value)

2. Flap

Flap span inboard position (BFI) = DFUS

Flap span outboard position (BFO) = BFOB x B
(where BFOB is an input value)

Flap inboard span ratio (BFIB) = BFI ÷ B

Flapped wing area:-

(SWFLAP) = $SREF \frac{(BFO - BFI)}{B} \left(+ \frac{(1 - TRW)}{(1 + TRW)}\right) \left(1 - \frac{(BFOB + BFIB)}{B}\right)$

Area of flaps (SFLAP) = SWFLAP x CFOC

(where CFOC is an input value)

3. Fuselage

Fuselage length (LF) = LF1 + LF2 + LF3

(where LF1, LF2 are input values and LF3 is a design variable)

Fuselage wetted area (SFWET)

$= 3.1416 \times DFUS \times (LF1 \times KW1 + LF2 \div LF3 \times KW3)$

(where the shape parameters KW1 and KW3 are program fixed data values. 0.75 are typical values for commuter aircraft fuselage shapes)

4. Empennage

(a) Vertical Tail

Tail arm (LV) = LF - LFAC (rear engine case)

$$\text{Tail area (SV)} = \frac{SREF \times B \times VV}{LV}$$

(where VV is fixed input data)

$$\text{Root chord (CVR)} = \frac{(SV \div ARV)^{0.5}}{(1 - TRV)}$$

(where ARV, TRV are fixed input data)

$$\text{Tail span (BV)} = \left(\frac{ARV}{SV}\right)^{0.5}$$

For wing mounted engines the tail arm is modified as here:-

$$\text{Tail arm (LV)} = LF - LFAC - 0.75\, CVR + \frac{BV}{2} \tan V$$

(where [tan V]is determined from input data)

$$\text{Mean geometric chord (MGCV)} = \frac{SV}{BV}$$

(b) Horizontal Tail

Tail arm (LH)' = LV (for low tail position)

$$\text{Tail arm (LH)}' = LV + \frac{BV}{2} \tan V \text{ (for T tail)}$$

$$\text{Tail arm (LH)} = LH' + \frac{BH}{4} \tan (WSWEEP)$$

(assumes tailplane sweepback angle - wing sweep)

$$\text{Tail area } SH = SREF \times MAC \times \frac{VH}{LH}$$

(where VH is a fixed input value)

$$\text{Tail root chord (CHR)} = \frac{(SH \div ARH)^{0.5}}{(1 + TRH)}$$

$$\text{Tail span } BH = \left(\frac{ARH}{SH}\right)^{0.5}$$

(where ARH, TRH are fixed input data)

$$\text{Mean geometric chord (MGCH)} = \frac{SH}{BH}$$

5. **Nacelle**

Wetted area (SNWET)

$$= 3.1416.\, DNAC.\, LNAC\left(0.5 + 0.135\ \frac{LN}{LNAC}\right)^{0.667}$$

$$\times\left(1.015 + \frac{0.3}{(LNAC/DNAC)^{1.5}}\right)$$

(where DNAC , LNAC are fixed input data)

C3 Mass Estimation

Accurate predictions of aircraft mass is always an essential requirement of aircraft project design methods. For optimisation, the mass predictions must include functions that represent influences of the design variables on component masses. Estimation methods are based mainly on previous designs which have been statistically correlated to provide generalised equations. These methods are drawn from available published data and directly supplied industrial contributions.

C3.1 *LOAD FACTOR EVALUATION*

The ultimate load factor (NULT) is used in the mass estimation model. It is equal to the limit load factor multiplied by the ultimate design factor (1.5 for civil aircraft). The limit load factor is the greater of the gust and manoeuvre factors. These load factors are determined in accordance with airworthiness requirements.[1] Using Howe's method the following relationships are adopted in the program:-

$$NGUST = 1 + \frac{6.3\, ARW.\, SREF.\, VDIVE}{MTO\,(2 + ARW)}$$

$$(NGUST)_{ULT} = NGUST \times 1.5 \qquad \_\_\_\_\_\_ 1$$

$$NMAN = 2.1 + \frac{10900}{4530 + MTO}, \text{ (or 2.5 whichever is greatest)}$$

$$(NMAN)_{ULT} = NMAN \times 1.65 \qquad \_\_\_\_\_\_ 2$$

NULT is the greater of 1 or 2 above

C3.2 *COMPONENT MASS PREDICTIONS*

The traditional approach to the evaluation of the aircraft maximum take-off mass is adopted in the program. In this, individual component parts of the aircraft (wing, fuselage etc) are separately assessed and then summed. The program outputs the aircraft mass breakdown in a conventional mass table. A detailed description of the estimation methods used for each component is given below:-

Aircraft maximum take-off mass (MTO)
= Aircraft zero-fuel mass (MZF) + Total fuel mass (MFUEL)

Total fuel mass = Reserve fuel + Mission fuel
Reserve fuel mass = Hold fuel (MFBHOL) + Diversion fuel (MFB3)

Hold fuel mass = Hold time (HOLDMN) x Fuel flow rate
The hold time is a fixed input parameter (see section C1 "Mission Requirements").
Fuel flow rate is set equal to the value determined in diversion cruise.

Diversion fuel mass = Diversion (climb + cruise + descent) fuel
Diversion fuel is calculated as an extra stage flown over the diversion distance (DIVERS). A detailed description of this method is given in section C8 ("Flight Profile Analysis").
The diversion distance is a fixed input parameter (see section C1).

Mission fuel mass = Stage (climb + cruise + descent) fuel
x Number of stages
+ Allowance for ground manoeuvres.
x Number of stages

Allowance for ground manoeuvres is an arbitary fuel mass to account for useage in taxiing, take-off acceleration, landing manoeuvres and standing. In discussion with industry it is set at 100 lb (45.35 kg) per stage.

For project aircraft design, stage fuel is traditionally estimated using a 'lost range' function. Since the flight profile is analysed in detail to determine optimum values the fuel used can be more accurately predicted (see section C8) and the lost range approximations avoided. The number of stages (INSTAG) and the stage distance (STAGE) are fixed input parameters (see section C1).

Aircraft zero-fuel mass (MZF)
= Aircraft operational empty mass (MOEM)+ Payload

Payload = Number of passengers (NPAS) x Payload mass per passenger (MPAY)

MPAY = Passenger mass + Baggage mass + Freight mass

The mixture of passengers and freight, and the baggage allowance per passenger will vary depending on airline operational requirements. For this reason a division between the payload components (passenger, baggage, freight) is not considered in the program.

After consultation with industry, the value of 200 lb (90.72 kg) suggested by Collingbourne[2] has been adopted. For operation over short-thin stages the operator may wish to carry freight in substitution to passengers up to the maximum aircraft mass. This aspect must be considered in the detail design of the fuselage, but for optimisation purposes the nature of this mixture is unimportant.

The number of passengers (NPAS) forms part of the fixed input data (see section C1).

Aircraft Operational Empty Mass (MOEM)

= Factor x (Aircraft Empty Mass (MEMPTY)

+ Operational items (MOP)

+ Crew mass (MCREW))

There is a wide variation in the requirements of different airlines with respect to operational items. To account for this, a factor is applied to the evaluation of operational empty mass. In the early studies this *factor* was set to 1.0 but in later study, after consultation with a specific potential commuter airline, a 5% allowance was added (i,e. 1.05). *Operational items* include passenger cabin supplies, water and toilet chemicals, safety equipment and baggage/freight handling equipment. An average allowance of 2 kg per passenger is adopted. *Crew mass* is composed of flight crew and cabin crew plus their baggage. For commuter aircraft of the size considered in these studies only two flight crew are necessary. The number of cabin crew is dependent on the number of passengers carried. A maximum of fifty passengers per cabin crew is specified by most airlines but the cost estimation is based on forty passenger as this is more often used in project used in project studies. Flight crew mass is set at 75 kg each. Cabin crew mass is set at 60 kg each.

Aircraft empty mass (MEMPTY)

= sum of all the aircraft "structural" component masses

= Wing mass + Fuselage mass + Nacelle mass + Empennage mass + Propulsion group mass + Undercarriage mass + Surface control mass + System mass + Furnishings mass

Furnishings mass (MFUR) includes passenger and crew seats, galleys, toilet, floor and wall covering, catering and water systems, cabin and flight deck furnishings. Complicated expressions are available[2] for the estimation of these items but there is a large variation between different airline standards and requirements and therefore this level of detailed analysis is not appropriate in this study. For short-haul, turbo-prop. designs[3] a value of 25 kg per seat was used, but to account for the potential for longer duration flights and passenger

expectation of higher standard for jet aircraft trim, the value is increased to 28 kg per seat (i.e. MFUR = 28 (NPAS + 3).
(Note, provision for cabin crew is set lower than that for the flight deck, therefore the value of 3 includes all extra seats.)

There is provision within the fixed input to alter furnishings mass estimation, (i.e. XXFURW, see section C1).

Systems mass (MSYS) is the sum of instrument mass, hydraulic and pneumatic systems, electrics, cabin conditioning, anti-icing and other miscellaneous items. Again complex relationships exist[2] to predict these components but since the standard and types of systems may vary between different aircraft purchasers it is sufficient to use a simple relationship in optimisation studies. The auxiliary power unit is a major element in the systems mass and since this is known in detail, the mass is added as a separate item.

$$MSYS = 0.075\ MTO + 140.0$$

Although this estimation falls at the lower end of the 14 to 8% range suggested by Torenbeek[4], discussion with industry suggests that current technology improvements will show substantial reductions in established systems.
The factor XXSYSW can be used to alter this value (see section C1).

Surface controls (MSURCO) includes all flight control systems mass. Again it is inappropriate to consider a more detailed analysis at the initial project design stage, therefore the expression suggested by Torenbeek[4] for transport aircraft is adopted without modification.

$$MSURCO = 0.64 \times (0.768)^{*} \times MTO^{.6667}$$
(* conversion to metric units).
The function may be altered by the XXCONW factor in fixed input data.

Landing gear mass (MUC) consists of main and nose gear units. For lighter aircraft (< 1000 Kg) it is necessary to evaluate these masses separately[3] but as aircraft size increases, the undercarriage mass relates more precisely to aircraft landing weight (or approximately MTO) Torenbeek[4] shows the undercarriage weights of several aircraft, in the commuter class (figure C1). For high wing aircraft, landing gear weight is increased. The expressions adopted in the program reflect the average value from figure C1 for low wing installations. A penalty of 0.5% MTO is added for high wing configurations to reflect increased complexity of the landing gear in such layouts.

MUC = 0.040 (MTO) (for low wing)
MUC = 0.045 (MTO) (for high wing)

These values may be altered by factor XXUCW in the fixed input data.

Propulsion group mass (MPRGR) is based on the bare engine mass. A factor of 18% is used to account for engine fitting, accessories, cowlings, noise supression material and thrust reversers. The engine scale factor is applied directly to this mass estimation.

MPRGR = Number of engines (INENG)
x 1.18 (bare engine mass (ENGM)) x Engine scale (ENGSC)

The number of engines is set at two in all the studies. Both ENGM and ENGSC form part of the fixed input data (see section C1).

The 18% factor may be modified by the use of the fator XXENGW in fixed input data.

Empennage mass (MEMP) is based on Torenbeek[4] normalised weight data (figure C2). Horizontal and vertical tail masses are evaluated separately and then summed. Tail areas (S_H) and (S_V) are evaluated in the geometry module (see Section C2 part 4). The coefficient is evaluated on a typical proportion of the two tail volumes.

$$MEMP = \frac{0.51\,(S_H + S_V)^{1.2} \times (VDIVE)}{(\cos(WSWEPD))^{0.5}}$$

Both VDIVE and WSWEPD are part of the fixed input data (see section C1). The original data on which the above function were based consisted of traditional metal constructed surfaces. To account for modern composite construction the mass is reduced by 20%:-

$$MEMP = 0.80\,(MEMP)$$

This factor was agreed with industry as representing current tail-surface manufacturing standard. This may be altered by the use of factor XXTAW in fixed input data (section C1).

Nacelle mass (MNAC) represented a difficult component for estimation. All the published methods of analysis considerably underestimated the industrially expected mass prediction. Torenbeek's method was shown to be low by a factor of approximately two. There may be many reasons for such discrepancies, not least of which may be the division of mass items between the propulsion group, wing group and nacelles. To resolve the difficulty a factor of 2.2 was arbitrarily applied to the Torenbeek formulae:-

MNAC = INENG x 0.055 (Engine Take-off Thrust (TOT) in "pounds")

The fixed input data factor XXNAW can be used to adjust this assumption if necessary. Engine take-off thrust (TOT) is automatically scaled with engine scale (ENGSC) elsewhere in the program. Both TOT and ENGSC form part of the fixed input data (section C1). The number of engines (INENG) is set at two throughout all the studies.

Fuselage mass (MFUS) estimating formulae found in references 4,5,6 give good estimations for commuter aircraft when adjusted for circular fuselage and known data. However, they all use different combinations of aircraft parameters. As no priority could be given to any method and to allow the optimiser to respond to each parameter, all three predictions are made and an average taken for use in the program. The formulea used are:-

1. Torenbeek

$MFUS = 0.23\ (SFWET)^{1.2}\ ((VDIVE \times LH/(2 \times DFUS))^{0.5}$

(where SFWET is calculated in the geometry section (C2), LH is the horizontal tail arm (a function of the design variable LF3,) DFUS and VDIVE are fixed input values).

2. Nicolai

$MFUS = 0.0737\ ((MTO \times NULT)^{0.286}\ LF^{0.857}\ 2\ DFUS \times VDIVE^{0.338})^{1.1.}$

(where LF is the overall fuselage length) a function of the design variable LF3.

3. Howe

$MFUS\ =\ 0.039\ (LF.\ 2.\ DFUS.\ VDIVE^{0.5})^{1.5}$

All these methods assume a conventional aircraft layout. The estimate is adjusted by +4% if the engines are rear-fuselage mounted, and by +7% if the main landing gear is directly attached to the fuselage structure.
The fuselage mass estimation can be adjusted using the factor XXFUW in the fixed input data.

Wing mass (MWING): several estimating methods were analysed[3] for commuter aircraft. The method described in reference 7 gave the best correlation with known wing data. Although this correlation was associated with a range of smaller aircraft than considered in the present study, the relationship is regarded as acceptable and compares well with industrial predictions for current fan-jet commuter designs using component mass 'build-up' methods. The coefficients have been adjusted to account for metric units and current design standards.

$$MWING = (X_1 + X_2 + X_3 + X_4 + X_5 + MFLAP)$$

where $X_1 = 4.2609 \times 10^{-3} (MTO \times NULT)^{0.591}$

$X2 = (SREF)^{0.715}$

$X_3 = (TCROOT)^{-0.607}$

$X_4 = (10 \times (1 + TRW)^{0.8} (ARW/10)^{0.436})$

$X_5 = (\cos (WSWEEP))^{-1.325}$

where SREF, TRW, ARW are design variables, NULT is calculated in the loading section (C3.1), TCROOT is a function of the design variable TCW and WSWEPD is the wing sweepback angle (input data).

Flap mass (MFLAP) is evaluated using the Torenbeek[4] method:-

$$MFLAP = 2.706 \times SFLAP \times KFLAP ((BFO\text{-}BFI)SFLAP)^{0.1875} \times \left(\frac{1.44\ VAIAS^2 \times 10^4 \sin (DFDLAN)}{TCW}\right)^{0.75}$$

where, BFO, BFI, SFLAP are calculated in the geometry section (C2).
VAIAS and TCW are design variables.
DFDLAN is the landing flap deflection (input data)
KFLAP is a coefficient to account for flap complexity
= 1.0 for single slotted
= 1.15 for double slotted
= 1.25 for single slotted with Fowler movement
= 1.30 for double slotted Fowler.

The wing mass was seen to underestimate the effect of torsional stiffness requirements. Legg[8] analysed the wing mass equations and suggested the following penalty function

$$GAMMA = 0.378 + \left(\frac{(0.0281 \times ARW \times SREF)}{(91.0 + 23.6 \times ARW)}\right)$$

(This penalty is not allowed to reduce below unity in the program)

$$MWING = MWING \times GAMMA$$

For aircraft with rear fuselage mounted engines the wing mass is increased by +5%, and for a fuselage mounted undercarriage a -5% factor is included.

C4 Aircraft Centre of Gravity and Balance Calculations

The program developed to analyse turbo-prop. commuter aircraft[3] included a section which evaluates aircraft centre of gravity positions for several loading cases. This procedure was adopted in the present work but modified to account for rear engine configurations, high and low tail options and the fan engine.

The forward c.g. position is selected from:-

1. Empty aircraft position
2. Zero-fuel condition with payload evenly distributed in cabin
3. Simplified window-seating rule (forward seats only)

The aft c.g. position is selected from:-

1. Empty aircraft position
2. Aircraft at MTO with 20% payload at rear of cabin (rear luggage hold)
3. Simplified window-seating rule (rear seats only)

It is recognised that these cases are arbitrary but they represent current practice. Greater knowledge on the position of baggage holds and the interior layout would be required if more detail was to be included in the estimation.

The forward position is used in the estimation of field performance and the aft position is used in the valuation of the stability constraint.

C5 Aerodynamic Analysis

The procedures for evaluating the aerodynamic coefficients are based on the methods described by Wolowicz[9] and coded for use in the turbo-prop. aircraft optimisation studies[3]. The original methods have been modified to remove the propeller effects, include compressibility effects, and suit fan-jet commuter design. The methods follow current aerodynamic analysis practice.
A brief description is presented below:-

1. Zero-lift drag of the aircraft is evaluated as the sum of the effects from each component, plus a factor to account for the interference at the wing/fuselage junction (interference drag at other junctions is assumed to be small):-

$$\begin{aligned}(CDO)_{Aircraft} = \Big[& (CDO)_{wing} + (CDO)_{vert.\ tail} + (CDO)_{horiz.\ tail} \\ & + (CDO)_{fuselage} + INENG(CDO)_{nacelle} \\ & + (CDO)_{interference} \Big]\end{aligned}$$

The wing, tailplane and fin effects are calculated from flat plate analogy with a correction for section thickness. All coefficients are referenced to the gross wing area (SREF):-

$$(CDO)_{wing} = 2\,(CF)_{wing}\,(1 + 2\,(TC)_{wing} + 120(TC)^4_{wing})\ SWX/SREF$$

$$(CDO)_{v.tail} = 2(CF)_{v.tail}\,(1 + 2(TC)_{v.tail} + 120\,(TC)^4_{v.tail})\ SV/SREF$$

$$(CDO)_{h.tail} = 2\,(CF)_{h.tail}\,(1 + 2\,(TC)_{h.tail} + 120\,(TC)^4_{h.tail})\,SH/SREF$$

where, areas SWX, SV, SH are calculated in the goemetry section (C2). Thickness ratio (TC) for the wing is an optimised variable. Tail thicknesses (TCV, TCH) are fixed input data. (CF) is the skin friction coefficient (see below).

For the fuselage and nacelles on commuter aircraft the base drag is assumed to be negligible. The usual axisymmetric body pressure drag term is used:-

$$(CDO)_{fuselage} = (CF)_{fuse.}\,[1 + 60/(LF/DFUS)^3 + 0.0025\,(LF/DFUS)]\,(SFWET/SREF)$$

$$(CDO)_{nacelle} = (CF)_{nac}\,[1 + 60/(LNAC/DNAC)^3 + 0.0025\,(LNAC/DNAC)]\,(SNWET/SREF)$$

where SFWET, SNWET are calculated in the goemetry section.

Fuselage length (LF) is an optimised variable.

DFUS, DNAC, LNAC are fixed input data.

Exact relationships for evaluation of the skin friction coefficients (CF) are difficult to establish, therefore the Prandtl-Schlichting theory for a fully turbulent boundary-layer is used together with a roughness factor to account for deviations from the theoretical shape and other surface irregularities. The Reynolds Number (REAVOP) used in the formula is the average value for the wing at mid-climb and cruise conditions. For non-wing coefficients this value is modified to suit a representative length of the component.

$$(CF)_{wing} = RUFW \times 0.455/(\log_{10}(REAVOP))^{2.58}$$

$$(CF)_{v.tail} = RUFW \times 0.455/(\log_{10}((REAVOP)\,(MGCV/MAC)))^{2.58}$$

$$(CF)_{h.tail} = RUFW \times 0.455/(\log_{10}((REAVOP)\,(MGCH/MAC)))^{2.58}$$

$$(CF)_{fuse.} = RUFF \times 0.455/\,(\log_{10}((REAVOP)(LF/MAC)))^{2.58}$$

$$(CF)_{nacelle} = RUFN \times 0.455/(\log_{10}((REAVOP)(LNAC/MAC)))^{2.58}$$

where, LF is an optimising variable,

MGVC, MGCH, MAC are calculated in the geometry section (C2)

LNAC, RUFW, RUFF, RUFN are fixed input data (see (Section C1)

The interference drag coefficient is calculated as:-

$$(CDO)_{int.} = 6.75 \times (CF)_{int.} \times (TCROOT) \times (CWR)^2/SREF$$

$$(CF)_{int.} = 0.455 \div \left(\log_{10}((REAVOP)(LFN/MAC))\right)^{2.58}$$

where LFN is an optimising variable.

TCROOT, CWR are calculated in the geometry section (C2)

2. *Aircraft lift* is evaluated in the usual way (i.e. by considering the 'aircraft-less-tail' (A-T) and adding the tail effect)

$$C_{L_{aircraft}} = C_{L_{(A-T)}} + C_{L_{H.Tail}} \left(\frac{SH}{SREF}\right)$$

Lift coefficient of the tail-less aircraft is determined by summing the effects from each aircraft component and modifying the total to account for mutual interference effects. Since the aircraft assumes different angles of attack (AOA) in various flight conditions it is easier to evaluate the lift curve slopes for the components and multiply by the appropriate AOA at each operational point. The assumption of linear lift curves is justified for the relatively shallow angles used in normal operations. The following relationship is evaluated:-

$$\left(\frac{dC_L}{d\alpha}\right)_{A\text{-}T} = K_1 \left(\frac{dC_L}{d\alpha}\right)_{exp.wing} \left(\frac{SWX}{SREF}\right) + \left(\frac{dC_L}{d\alpha}\right)_{fuse} \left(\frac{SFX}{SREF}\right)$$

$$+ \; INENG \left(\frac{dC_L}{d\alpha}\right)_{nacelle} \left(\frac{SNX}{SREF}\right)$$

SFX, SNX are the fuselage and nacelle maximum cross sectional areas:-

$$SFX = \frac{\pi}{4}(DFUS)^2; \qquad SNX = \frac{\pi}{4}(DNAC)^2$$

SREF is the lift coefficient reference area (gross wing area)

Factor K_1 accounts for wing/fuselage interference effects. For a conventional circular fuselage it can be evaluated as:-

$$K_1 = 1.0 + 2.25\,(DFUS/B)$$

where DFUS is a fixed input value

B is the calculated wing span.

The component lift curve slopes are evaluated as:-

$$\left(\frac{dC_L}{d\alpha}\right)_{exp.wing} = f\left[\frac{ClA}{E + \dfrac{ClA}{ARW \times \pi}}\right]$$

Factor f is assumed 0.995 for conventional tapered wings.
(C1A) is the basic sectional lift curve slope (an input value)
(ARW) is the wing aspect ratio (an optimisied variable).
Factor E is the Jones velocity factor, calculated for straight tapered wings as:

$$E = 1 + (2 \times TRW/(ARW(1 + TRW)))$$

Lift curve slopes for the fuselage and nacelle are evaluated using the graph of $(K_2\text{-}K_1)$ against body length/diameter ratio(9) which has been curve fitted in the program

$$\left(\frac{dC_L}{d\alpha}\right)_{fuse} = 2 \cdot (K_2\text{-}K_1)_{fuse} \left(\frac{SFX}{SREF}\right)$$

$$\left(\frac{dC_L}{d\alpha}\right)_{nacelle} = 2 \cdot (K_2\text{-}K_1)_{nacelle} \left(\frac{SNX}{SREF}\right)$$

At a given aircraft lift coefficient (C_{L_A}) the proportion attributed to the horizontal tail is assumed to be:-

$$C_{L_{H.Tail}} = \frac{C_{M_{AC}}}{VH} + \frac{C_{L_A}}{VH}\left(\frac{X_{CG} - X_{AC}}{MAC}\right)$$

VH is the horizontal tail volume coefficient which is a fixed input value
$(X_{CG} - X_{AC})$ is the distance between the aircraft centre of gravity and the aerodynamic centre. (X_{CG}) is determined at a representative loading condition in the aircraft balance calculations.

$$(X_{AC}) = (XAC)_{wing} + (XAC)_{fuselage} + (XAC)_{nacelles}$$

(XAC) is calculated as LFAC in the geometry section
$(XAC)_{fuselage}$ is the forward shift due to the body

$$= -\left[\frac{1.8\ DFUS^2.LFN}{\left(\frac{dC_L}{d\alpha}\right)_{(A-T)} SREF}\right]$$

LFN is position of the wing as calculated in the geometry section
$(XAC)_{nacelles}$ is evaluated in a similar fashion:-

$$= K_{nac}\left(\frac{DNAC^2.\ LN}{\left(\frac{dC_L}{d\alpha}\right)_{(A-T)}.SREF}\right) \times \text{INENG}$$

K_{nac} = -4.0 for wing mounted engines
= 2.5 for rear fuselage mounted engines
LN is the position of the nacelle as calculated in the geometry section
$C_{M_{AC}}$ is the aircraft pitching mount coefficient about the aerodynamic centre.
$C_{M_{AC}} = CM_{WING} + CM_{fuselage}$
(CM_{WING}) is an input value (CMARCW)

$(CM_{fuselage})$ is obtained from Munk's theory

$$= - \left(\frac{1.8\,(1 - 2.5\ DFUS/LF)\ \pi\ (DFUS)^2\ LF}{SREF \times MAC \times 4} \right) \times (FINCIR)$$

(FINCIR) is the body/wing setting angle - a fixed input value.
Hence:-

$$C_{L_{(A-T)}} = C_{L_A} - C_{L_{HTail}} \left(\frac{SH}{SREF} \right)$$

Then angle of attack of aircraft can be evaluated as:-

$$\alpha = \left(C_{L_{(A-T)}} + \left(\frac{d\,C_L}{d\alpha} \right)_{fuse} (FINCIR) \right) / \left(\frac{d\,C_L}{d\alpha} \right)_{A-T}$$

Lift from each component can be calculated:-

$$C_{L_{nacelle}} = \left(\frac{d\,C_L}{d\alpha} \right)_{nacelle} \cdot \alpha$$

$$C_{L_{fuselage}} = \left(\frac{d\,C_L}{d\alpha} \right)_{fuselage} \cdot \alpha$$

$$C_{L_{wing}} = C_{L_{A-T}} - C_{L_{nacelle}} - C_{L_{fuselage}}$$

3. *Lift induced drag* is calculated as the sum of the component parts plus interference effects

$$CDI = (CDI)_{wing} + (CDI)_{h.tail} + (CDI)_{fuse} + (CDI)_{nacelles}$$

$$+ (\Delta CDW) + (CDI)_{interference}$$

where

$$(CDI)_{wing} = C^2_{L\ wing} \ \frac{(1 - \delta)}{\pi\ ARW}$$

where δ is a parameter evaluated from a graph of ARW, TRW given in ref.14, and curve fitted in the program

$$(CDI)_{h.tail} = C^2_{L_{h\ tail}} \cdot \frac{1.2}{\pi (ARH)} \left(\frac{SH}{SREF} \right)$$

(i.e. assuming an Oswald factor of 1.2 for the tailplane)

$$(CDI)_{fuselage} = C_{L_{fuselage}} (\alpha - (FINCIR))$$

$$(CDI)_{nacelles} = C_{L_{nacelles}} \cdot \alpha$$

(ΔCDW) is the increment in profile drag due to angle of attack

$$= \frac{0.75\ X}{(C1\ MAX - C1\ DES)^2} \left(C_{L_{wing}} - C1DES \right)^2$$

where:

$$X = 67 \frac{C1MAX}{(\log_{10} R.)^{4.5}} - .0046 (1 + 2.75\ TCW)$$

R = Reynolds number of wing at stall

$(CDI)_{interference}$ is evaluated by Munk's Stagger Theorem

$$= \left(\frac{2\sigma}{\pi}\right) C_{L_{wing}} C_{L_{HTail}} \left(\frac{SH}{B.BH}\right)$$

where σ is evaluated from curve fitted data with downwash gradient and ratio (BH/B) as the coordinates. The downwash factor evaluation in the program accounts for high and low wing and high and low horizontal tail positions.

4. *Compressibility effects* usually involve the evaluation of a set of complex relationships involving flight and local Mach numbers, lift coefficients and sectional geometry. Edwards developed a simplified procedure using ESDU data 71019 for use in the MVO work at RAE (Appendix B of ref.2). This method has been included and is briefly described here:-

Aerofoil drag-rise mach number:-

$$MD = \frac{A' - C_{L_D}}{A''}$$

C_{L_D} = lift coefficient at drag rise

A' = (2.78 + 2.03 (ROOF)) + (12.68 + 3.87 (ROOF)) TCW

A" = (2.65 + 2.25 (ROOF)) + 27.8 TCW

For civil transport aircraft the drag rise of finite swept wings is:-

$(CDC) = 0.007\ \Delta + 155\ \Delta^{4.5}$

$\Delta = 0.003 + MACH - MDES$

where MDES is the free stream mach number at drag rise:-

$$MDES = \frac{MD}{\cos (WSWEP)}$$

MACH is the flight Mach number which is evaluated from the flight profile speed/altitude optimisation.

To account for swept wing effects on aerofoil drag rise, wing thickness (TCW) is multiplied by $(\cos (WSWEP))^{-1}$ and C_{L_D} by $(\cos (WSWEP))^{-2}$ in the above equation. In order to reflect the increase in lift coefficient on the wing due to trim effects C_{L_D} is approximated to $C_{L(A-T)}$.

5. *Total aircraft drag* at each flight condition is determined by transferring the aerodynamic coefficients to a subroutine (AER01) which evaluates the aircraft angle of attack and then computes the total aircraft drag (and lift). This value is then passed back to the aircraft performance estimation program. It is unnecessary to determine the aircraft lift-drag polar in the normal way for performance analysis, but for completeness of output data, a table of C_L, C_D against AOA is presented.

Hence:- $CD_{(TOTAL)} = (CDI) + (CDO) + (CDC)$

6. *Flap effects* were developed as part of the earlier turbo-prop. optimisation studies[3]. The methods are based on theories described by Torenbeek[4]. The only modifications made for the turbofan program is to remove the original power (propeller wash) effects. Any one of four different flap configurations can be chosen:-

IFLAP 1 = Single slotted with simple pivot
2 = Double slotted with simple pivot
3 = Single slotted with Fowler movement
4 = Double slotted with Fowler movement

Take-off flap deflection is one of the optimised variables. Landing flap deflection is a fixed input value. Two subroutines are used for general predictions. FLAP1 determines all the parameters which are independent of flap deflection. FLAP2 determines the parameters dependent on flap angle. The main program evaluates the lift coefficient for the whole aircraft in the take-off and landing configurations. This includes correction to account for tailplane trim download. The associated stall speeds for take-off and landing are calculated and the take-off speed (V2) determined for use in BFL and WAT performance estimations.

7. *Summary.* All the aerodynamic routines were checked against known lift/drag polars for actual commuter aircraft and found to predict values within acceptable accuracy.

C6 Stability Assessment

Simple stability calculations for the aircraft are necessary to allow evaluation of the static margin constraint. This constraint ensures a pre-set value relative to the aft centre of gravity position:-

$$\text{Static Margin} = (X_{NP} - X_{aft}) / MAC$$

The centre of gravity position (X_{aft}) is determined as part of the balance calcuations (Section C4).

The position of the aircraft neutral point (X_{NP}) is:-

$$X_{NP} = X_{AC} + MAC \left[\left(\frac{dC_L}{d\alpha}\right)_{HT} / \left(\frac{dC_L}{d\alpha}\right)_{AC} \right] . \left(1 - \frac{d\varepsilon}{d\alpha}\right) . VH$$

where VH is the horizontal tail value (a fixed input value)

$\left(\frac{dC_L}{d\alpha}\right)_{HT}$ is the lift curve slope of the horizontal tail (section C5)

X_{AC} is the aerodynamic centre position of the aircraft (see C5)

$\left(\frac{dC_L}{d\alpha}\right)_{AC}$ is the lift curve slope of the whole aircraft

$$= \left(\frac{dC_L}{d\alpha}\right)_{A\text{-}T} + \left(\frac{dC_L}{d\alpha}\right)_{HT} \cdot \left(\frac{SH}{SREF}\right) . \left(1 - \frac{d\varepsilon}{d\alpha}\right)$$

where

$\left(\frac{dC_L}{d\alpha}\right)_{A\text{-}T}$ is the lift curve slope of the aircraft minus tail (see C5)

$\frac{d\varepsilon}{d\alpha}$ is the downwash gradient evaluated using the Torenbeek equation:-

$$\frac{d\varepsilon}{d\alpha} = \frac{1.75 \left(\frac{dC_L}{d\alpha}\right)_W}{\pi \, ARW \, (TRW \times F_r)^{0.25} \, (1 + F_M)}$$

where

$\left(\frac{dC_L}{d\alpha}\right)_W$ is the lift curve slope of the wing (section C5)

ARW is the wing aspect ratio (section C2)

TRW is the wing taper ratio (section C2)

F_r is the tail arm factor $= 2 \times \frac{LH}{B}$

F_m is the factor which depends on the separation of the tail and wing surfaces, it is evaluated for high and low positions of wing and tail.

The stability constant is used to position the longitudinal location of the wing and size the tail area for optimum configuration.

The static margin for the aircraft in the datum c.g. position (half loaded) is also evaluated and quoted in the output.

C7 Engine Data

The handling of engine data for the fan engines represents a major change from the earlier turbo-prop.work undertaken at Loughborough. The original optimiser included simplified closed-form equations to model engine and propeller performance. Turbofan engines need more extensive functions to simulate the variable nature of their performance at different flight conditions. Generalised equations were not considered accurate enough for studies on turbofan aircraft.

The first series of optimisation were based around the CFE 738 engine. This is a joint venture engine between General Electric and Garrett started in 1985.[10] Earlier market analysis indicated the future need for an engine to suit the growth in the business jet market. Such medium sized aircraft (25-35000 lb MTOW) would require two engines of about 5500 lb to thrust. The engine core, H.P. turbine and fan are similar to the successful GE 27 engine. The engine has a by-pass ratio of 5.3 giving a take-off thrust of 5600 lb with SFC of 0.39 and a cruise thrust (40K, 0.8M) of 1310 lb at SFC .645. Fan diameter is 34.5 ins and length is 65 ins. The engine is to be available from the end of 1990.

The manufacturers provided a tabular print-out of Thrust and Fuel Flow values for various engine/aircraft operating conditions. Four ratings were specified:-

IRATIN = 0 - maximum continuous cruise
1 - maximum continuous climb
2 - take-off
3 - flight idle.

For optimisation search methods it is preferable to use continuous functions which have smooth first and second-order derivatives. To this end the engine data was regressed using a commercial statistics program. It was found necessary to use a seventh-order polynominal to curve-fit the data against altitude but a quadratic function against Mach number was acceptable.

The generalised relationship are specified as:-

(coeff a) = $a_o + a_1\ h + a_2\ h^2 ....a_n\ h^n$

(coeff b) = $b_o + b_1\ h + b_2\ h^2\ ....b_n\ h^n$

(coeff c) = $c_o + c_1\ h + c_2\ h^2\ ....c_n\ h^n$

Thrust = (coeff a) + (coeff b)M + (coeff c) M^2

(Similarly for Fuel-flow)

The eight sets of coefficients (a_i, b_i, c_i) for engine ratings 0, 1 and 3 were stored in subroutine DATAIN. Transfer to the thrust and fuel flow functions (THRUST1, FULFLO1) is made through common blocks (thdata, ffdata). Altitude varied from 0 to 50000 ft. To normalise the coefficient values, the height term in the above relationships was modified to:-

$$h = \left(\frac{\text{altitude}}{25000}\right) \text{ ft.}$$

The take-off data includes air temperature (TEMP+ISA) as an extra variable. Values include ISA - 10, 0, +10, + 20, + 30, + 40 and (by averaging the 20/30 values) the often specified +25°C. It was found that the polynominal curve fit in altitude could be reduced to a quadratic without significant loss of accuracy for the take-off setting.

Thrust setting (TSET) can be adjusted in the cruise rating. Thrust values are directly proportional to the setting values.
The arguments of the THRUST and FULFLO functions are:-

1. Altitude
2. Airspeed (TAS)
3. Rating (during variable 0, 1, 2, 3)
4. Temperature (Take-off only)
5. Thrust Setting (1.0 to 0.25, cruise only)

In later studies the Rolls Royce/Allison engine (RB 580) was used. This is another new engine developed to suit the commuter market. It has a similar layout to the CFE engine and also has a bypass ratio of about five. It is more powerful (thrust 6800 lb) and offers considerably more development potential (up to 9500 lb thrust within six years).

It was found to be impossible to curve-fit the tabulated R.R.data[11] with the type of polynominal functions used for the CFE engine. The data between 20000 and 35000 ft shows a substantial discontinuity. The only technical explanations available for this effect were related to fan performance and the advanced engine management system. For some studies it was possible to use a set of three dimensional linear interpolation routines (Function LININT) on the tabulated data. This determines thrust and fuel flow for any combination of altitude, Mach number and engine setting (climb, cruise 100%, 75%, 50%, 25% and flight idle).

In some cases this interpolation method proved to be too unstable for the search techniques used in RQPMIN. It was decided that the original CFE data should be scaled to simulate the RR 580 engine. A scaling factor applied to the whole set of data showed an overestimate in climb, cruise and flight idle. Also,the thrust and fuel flow are not equally proportional in scale. The early studies showed the critical operating regions to be at take-off and cruise. To obtain a better match of the data from the two sets of engine data, it was decided to use different scaling fators for each operating condition. The tabulated data was used to determine these scaling factors, thus:-

a) Take-off Rating (Static SL - ISA)

RR Thrust	6797 }	
CFE Thrust	5564	**Thrust Scale = 1.2216**
RR Fuel flow	2377 }	
CFE Fuel flow	2110	**Fuel flow Scale = 1.126**

b) Climb (max.continuous) at MN = 0.6

Height 5K	RR Thrust	3584 }	
	CFE Thrust	3068	Scale = 1.1681
Height 15K	RR Thrust	3037 }	
	CFE Thrust	2626	Scale = 1.1565
Height 30K	RR Thrust	2223 }	
	CFE Thrust	1942	Scale = 1.1447

Thrust Average Scale = 1.156

Height 5K	RR Fuel flow	2329 }	
	CFE Fuel flow	2067	Scale = 1.1139
Height 15K	RR Fuel flow	1858 }	
	CFE Fuel flow	1668	Scale = 1.1031
Height 30K	RR Fuel flow	1273 }	
	CFE Fuel flow	1154	Scale = 1.1267

Fuel flow Average Scale = 1.1146

c) Cruise (maximum continuous, 100% thrust setting)

(Height 30K,	MN = .8)	
RR Thrust	1920 }	
CFE Thrust	1714	Scale = 1.1202
RR Fuel flow	1241 }	
CFE Fuel flow	1146	Scale = 1.083
(Height 30K,	MN = .6)	
RR Thrust	2054 }	
CFE Thrust	1824	Scale = 1.1261
RR Fuel flow	1169 }	
CFE Fluel flow	1083	Scale = 1.079

Thrust Average Scale = 1.1231

Fuel flow Average Scale = 1.0810

The optimiser is used with the above scales automatically applied when the RR-engine is selected. The engine routines include a dummy variable, (IENTYP) to select either (1 =) CFE engine or (2 =) RR 580 engine

To allow the aircraft studies to anticipate future engine development an overall scale factor on the engine can be utilised (ENGSC). This factor has been used in the studies to show the effects of increasing the thrust of the input engines, and to investigate generalised engine/airframe matching. In this way it has been possible to consider 'rubberising' the engine data.

C8 Performance Estimations

Aircraft Performance is estimated for:-

(1) Flight profile analysis

(2) Field performance

The methods are similar to those developed in the original turbo-prop. studies but modified to suit turbofan engine details and pressurisation descent restrictions.

C8.1 *FLIGHT PROFILE ANALYSIS*

This analysis uses the same methods as developed in the original SCOPE program [8] and modified in the CASTOR program.[12] The SEGMENT and ASTAGE subroutines have been modified to substitute calls to the new fan-jet engine data in place of the engine power and propeller analysis previously used.

The three phases of the flight profile (climb, cruise and descent) are analysed separately and summed to determine the flight parameters. Climb and descent paths are considered by analysing a series of equal height segments. The cruise phase is segmented in equal distance steps. Detail changes in aircraft mass, air density, speeds and time are accounted for at the mid-segment position. The number of segments in climb/descent and cruise is selected as fixed input data (INHSEG, INCSEG), as shown in fig C3. Ground and near-ground manoeuvres (taxi, take-off, approach and landing) are not analysed in this method, but an allowance is made for fuel and time used in the overall assessment.

For commuter aircraft, it is common practice to undertake multi-stage flights. The possible combinations of numbers of stages and stage distances is infinite. The flight profile analysis method could be designed to account for some of these possibilities, but for simplicity it is assumed that all stages are of the same length. The number of steps and stage lengths are fixed input values. It would be possible to analyse each stage sequentially and sum the total effect but this would require extra variables and constraints to be added to the problem and it would increase computation time. The approach developed in SCOPE was used. In this, the first stage is fully analysed together with a 'notional' stage at an assumed reduced aircraft weight. A linear interpolation is used to estimate the time and fuel used in each actual stage. The accuracy of this approximation was checked[12] and found to be acceptable for multi-stage profile of 600n.m. and less. This approximation was based on longer range capabilities than considered for current designs and was therefore retained as a valid procedure in the new program.

The diversion stage is handled in the same way as in CASTOR (i.e. the climb and descent speeds are assumed to be the same as the main stage and only the cruise height, speed and throttle setting are considered as design variables). This procedure, although producing slightly higher fuel burn than a true optimum, has been shown(12) to be within the overall mass estimation tolerance. For short stage lengths the optimum flight path would be a 'saw-tooth' profile with no cruise phase. To avoid operational difficulties in the optimisation method, and to rationalise the true flight operation practice in which the climb trajectory would be more gradually transferred to the descent, a minimum cruise distance is imposed. This is achieved by the lower limit set on the cruise length variable (typically 20% stage distance). For longer stages this problem does not occur because of engine thrust reduction in the tropopause.

The optimiser will select the aircraft airspeed in descent to be as fast as possible. This could lead to unacceptably high values for rate of descent. The maximum descent rate may be limited by the speed of repressurising the cabin.
The minimum time of descent

$$= \left(\frac{\text{cabin altitude}}{\text{maximum rate of repressurisation}}\right) - \text{ground time allowance}$$

Maximum rate of repressurisation is assumed to be 400 ft/min.
Ground time allowance (includes landing, taxi and stand time) = 3.1 min.

$$\text{Cabin altitude} = \frac{\left[1 - \left(\frac{\text{cabin pressure}}{\text{ISA-SL pressure}}\right)^{\frac{1}{5.2561}}\right]}{0.02256}$$

Cabin pressure = Cruise altitude ambient pressure + cabin differential pressure
Cabin differential pressure is assumed to be 8.2psi
Cruise altitude ambient pressure = 1 - 0.022256 cruise altitude
Cruise altitude = HCRUZ, (an optimising variable).

Discontinuities in speeds between the various phases was investigated in the CASTOR(12) work. It was found that the 'energy correction' imposed in the earlier work had little influence on the optimiser result. These correction functions have not been used in the current program, although it is recognised that such discontinuities would occur in flight trajectories if flown in the manner described by the program. Actual flight trajectories would not involve these effects due to smoothing at the transitions.

The flight profile analysis allows the following parameter to be optimised:-

1. Climb speed
2. Climb distance
3. Cruise speed
4. Cruise engine setting
5. Cruise altitude
6. Cruise distance
7. Descent speed
8. Descent distance
9. Diversion altitude
10. Diversion speed
11. Diversion cruise setting
12. Diversion cruise distance

The following constraints are imposed, in addition to the minimum and maximum values on the above variables,

1. Total distance (climb + cruise + descent) must equal the input stage distance (STAGE)
2. Total diversion distance (climb + cruise + descent) must equal the input diversion distance (DIVERS)
3. Cruise Mach number must not exceed 0.85
4. Descent speed must not exceed cruise speed.
5. Descent time must not be less than the minimum time for cabin pressurisation

The flight profile analysis outputs the fuel used in each stage (including diversion). These are summed and an allowance of 100lb per stage added for ground manouvres. The fuel used in the 'holding' stage is calculated assuming the same fuel flow rate as predicted in the diversion cruise phase. Hold time is a fixed input value. The method also outputs the average stage time for the prediction of block time (used in cost estimations).

The climb phase is performed with the engine at the maximum continuous climb rating. The cruise phase is performed with the engines in the cruise rating at whatever thrust setting is optimum.
The descent phase is performed at flight idle setting.

C8.2 *FIELD PERFORMANCE*

Field performance in aircraft project design is conventionally assessed using step-integration analysis of the equation of motion of the aircraft. This is not possible in optimisation methods because these techniques are computer-time consuming and many iterations would be required. It is necessary to use less accurate, but quicker, closed-loop methods.

For **balanced field length** (BFL) the equation recommended by Torenbeek[4] is used with the coefficients adjusted to suit speciman (known) data points for the type of aircraft under consideration:-

$$BFL = \left(\frac{0.704}{1 + 2.3\,(GRAD2 - 0.024)}\right)\left(\frac{MTO}{(SREF)(CLV2)} + 14.0\right) \times \left(\frac{9.81\,(MTO)}{0.8(TOT)(INENG)} - 0.04 + 2.7\right) + 200$$

GRAD 2	=	the second segment climb gradient (ISA)
(0.024)	=	the minimum airworthiness gradient for two engine aircraft.
(CLV2)	=	the aircraft lift coefficient at speed V_2
(14.0)	=	screen height (i.e. 50ft)
TOT	=	take off thrust rating per engine
(0.04)	=	runway friction coefficient including aerodynamic effects
(200)	=	typical inertia distance for 4.5 second control delay

Estimation of **landing field length** (LFL) is based on Loftin[13] analysis:-

$$LFL = \left(5.612\,\frac{MLAND}{SREF \times CLMTRL} + 153.0\right) \times 1.667$$

MLAND can be selected in the program by a control parameter IMLAND =

1 = MTO
2 = MTO - mission fuel
3 = Zero fuel mass
4 = MTO - first stage fuel only

CLMTRL= Maximum lift coefficient for the aircraft trimmed in the landing configuration.

(1.667) = the required airworthiness multiplying factor.

The **second segment climb gradient** with one engine inoperative is required in the evaluation of balanced field length. This calculation is performed at ISA conditions. It is also necessary to determine the second segment gradient at the WAT limit conditions (i.e. ambient temperature [WATISA] and airfield altitude [WATH] which are input as fixed data). Aircraft speed is fixed at V_2 (climb safety speed) and the engine is at continuous climb rating. For some engine designs an increase in thrust is allowed (emergency boost, EMBST). This is a fixed input value.

Thrust = Thrust x EMBST

The basic drag of the aircraft is evaluated using the procedures of AERO1 and FLAPS for the aircraft at sea level, speed V_2 and with flaps at the take-off deflection (DFDTO which is an optimising variable).

Drag increase due to asymmetic flight following an engine failure is estimated using methods described by Torenbeek[9]:-

$$\Delta C_D = \Delta C_{D_{SE}} + \Delta C_{D_{SAS}}$$

$\Delta C_{D_{SE}}$ is the increment in drag area due to the windmilling engine. For modern fan-jet engines, with the engine inlet diameter assumed to be 85% DNAC, the nozzle diameter at 60% DNAC, and the nozzle to free-stream velocity assumed as .92, the increment is estimated as:-

$$CDSE = 0.0785 \times 0.7225\ DNAC^2 + \frac{0.1472 \times 0.7854 \times 0.36\ DNAC^2}{(1 + 0.16MACH^2)}$$

$\Delta C_{D_{SAS}}$ is the increment in drag of the aircraft due to asymmetric flight (yaw effects). The pilot may select several different bank/sideslip attitudes[14]. This makes estimation of this drag increase difficult and potentially inaccurate. For airworthiness flight demonstration some of this variability is removed. Torenbeek[4] suggest the following estimation for jet powered aircraft.

$$CDSAS = K_s \left[\frac{Thrust}{\frac{1}{2}\rho\ SV^2} + CDSE \right]$$

$$K_s = \left(\frac{BE}{LV}\right)^2 \frac{1}{SV} \frac{1}{\pi.ARV} \left[1 + 2.3 \times 0.67 \left(\frac{ARV}{\cos(VSWEP)} \right)^{-0.33} \right]$$

BE is the spanwise engine thrust line offset distance (ENGLOC) a fixed input value.

VSWEP is the sweepback angle of the fin (a fixed input)

To account for the induced drag increase due to maldistribution of wing spanwise loading, an arbitrary 10% increase is applied:-

$$\Delta D_{D_I} = DCDI + \frac{0.1 \times 1.5 \times C_{L_{To}}^2}{\pi\ ARW}$$

where 1.5 is the estimated approximation of the Oswald factor.

Hence, total drag:-

$$C_{D_{TOT}} = (QV2)(SREF)\left[CDV2 + DCDI + \frac{(CDSE + CDSAS)}{SREF}\right]$$

where,

QV2 is the dynamic pressure at speed V2

CDV2 is the aircraft total drag at speed V2 (determined in subroutine AERO 1).

Climb gradient is evaluated as:-

$$\text{Gradient} = \frac{\text{Thrust - Drag}}{\text{MTO x 9.81}}$$

At ISA conditions : Gradient = GRAD2.

At WAT conditions : Gradient = WATGRA and is compared with airworthiness minimum gradient (GRAMIN). For twin-engined aircraft of the commuter type this is set at 0.024 and forms one of the optimiser constraints.

C9 Aircraft Cost Analysis

Aircraft cost analysis forms an essential part of the design method because the most commonly chosen optimising function is direct operating cost per flight. For civil aviation each airline (and manufacturer) has developed their own methods of assessing operating expenses. These methods reflect the type of operation, flight patterns, aircraft fleet mix and accountancy practices of the particular company. In general, the expenses not directly attributed to the flying cost *(Indirect Operating Cost IOC)* are so variable that it is impossible to develop a unified estimating procedure. It is difficult to assign these costs to the aircraft design parameters, therefore it is common practice to ignore them for project design studies.

In the past, several standard methods (15) (16) (17) (18) have been used to estimate direct operating cost (DOC). Although all these methods are slightly different they all identify the cost under four broad headings:-

(1) Standing charges
(2) Maintenance costs
(3) Flight cost.
(4) Cost parameters

Each heading comprises several component costs (fig.C4)

In an inflationary economic climate, cost evaluation is highly time dependent. The methods developed in this program have been related to mid-1987 prices. Although it was thoroughly researched, an index for inflation which gave a satisfactory account for these increases could not be found. In many aircraft studies it is sufficient to consider the relative costs of each design with the absolute cost figure being less significant. The method of analysis used in the program was checked against a more detailed industrial (Short Brothers) estimate and shown to be in good agreement (in 1987).

A detailed description of the method is given below under the same broad heading as referred to above.

C9.1 *AIRCRAFT STANDING CHARGES* (COSTSC) comprise:-

(a) Depreciation of the capital investment

(b) Insurance costs

(c) Interest charges on capital employed

Interest charges are regarded as too variable to be accurately included in the program and are often considered as falling outside the influences of the manufacturing/design activity. They are therefore not represented in the following relationship:-

$$\text{COSTSC} = \left[(1 + \text{SPARES}) \times \text{JCSC1} + \text{JCSC2} \right] \times \text{PAC} \times \left[\frac{(\text{TBLOCK} + \text{TADMIN})}{\text{UTILISATION}} \right]$$

where

SPARES is the capital required to cover the cost of spares holding (assumed to be 15%)

JCSC1 is the percentage depreciation per year

$$= \left(\frac{\text{Initial price - Residual price}}{\text{Initial price}} \right) \div \text{Depreciation Period (years)}$$

Depreciation is calculated over a 12 year period to a residual value of 15% but may be changed by adjusting the fixed input value of JCSC1.

JCSC2 is the insurance rate (%). Assumed to be 1.5% but may be altered by changing the fixed input value.

PAC is the initial aircraft price with engines and equipment (see below for full analysis).

TBLOCK is the flight (stage) block time = (TFLT) + 3.1 minutes for air manoeuvres + 4.0 minutes for ground manoeuvres.

TFLT is the sum of times from each segment of the flight profile for one stage.

TADMIN is the time allowance for scheduling and other non-flight time loss (assumed to be zero in this program).

UTILISATION is the aircraft annual utilisation. For short-haul turbofan commuters this is assumed to be 2500 hours.

Aircraft price (PAC) estimation is required for the evaluation of depreciation.

Methods employing regression techniques on known aircraft data have been proposed[20][21] but the added complexity of these methods does not necessarily translate into improved accuracy for the estimation. It was therefore decided to use a simpler type of model:-

PAC = Price of airframe and system (PAF) + Price of engines (PENG)

The original turbo-prop studies incorporated a cost model which was shown to slightly underestimate current commuter airframe prices. Analysis of "Interavia Commuter Aircraft Directory - March 1987" involving 14 aircraft in the 19 to 107 seat range, showed that aircraft operational mass was the best parameter on which to base price estimation. The average cost per Kg was calculated at $653

Hence:

PAF = MOEW x 653.0

Engine price is estimated from RR engine price data (1984 updated to mid '87), by the following relationship:-

$$PENG = INENG\ (0.38 + 1.02 \times 10^{-4} \times TOT)\ 10^{6}$$

where

INENG is the number of engines

TOT is the engine take-off thrust (in lb)

TOT = TOT x ENGSC

C9.2 *MAINTENANCE COST* (COSTM) is assumed to be the sum of airframe maintenance, engine maintenance and an allowance to cover the maintenance burden costs.

COSTM = COSTAM + COSTEM + COSTMB

Evaluation of these costs has always presented difficulty due to the variability of the maintenance tasks on different components of the aircraft. All the standard DOC methods include relationships for estimating these costs. Hofton[21] attempted to rationalise these procedures in his Cranfield Cost Study, but the relationships used in the program are based on procedures developed by Short Brothers over the past ten years:-

Total airframe maintenance (COSTAM) is the sum of labour (CAL) and material (CAM) cost:-

COSTAM = CAL + CAM

Labour cost is evaluated as a fixed cost related to the flight stage and an hourly cost:-

CAL = (KFCA + KFHA x TFLT) x LR

where

KFCA is the labour cost per stage length:-

$$= 0.05 \left(\frac{WA}{1000}\right) + 6.0 - \left[\frac{630}{\left(\frac{WA}{1000}\right) + 120} \right]$$

KFHA is the labour cost per flying hour = 0.59 x KFCA

LR is the labour pay rate (assumed to be $20 per hour)

WA is the weight (lb) of empty aircraft less engines:-

= (MEMPTY - MPRGR) x 2.205

Material cost is likewise stage and hourly dependent:-

CAM = CFCA + CFHA x TFLT

where:-

CFCA is the material cost per stage length:-

= 6.24 x ($PAF/10^6$)

CFHA is the material cost per flying hour:-

= 3.08 x ($PAF/10^6$)

Total engine maintenance cost per hour (COSTEM) is based on the actual costs of the CFE-738 engine, suitable scaled for engine size:-

COSTEM = 120.0 (TBLOC) x ENGSC

Total maintenance burden (COSTMB) is associated with the overhead cost of providing the maintenance facility. A standing charge and an hourly cost are used as the predictors:-

COSTMB = 25.3 + (51.1 x TBLOC)

C9.3 *FLIGHT COSTS* are assumed to consist of:-

3.1 Crew cost (COSTC)

3.2 Fuel and oil usage (COSTF)

3.2 Landing and navigation fees (COSTLF)

3.1 *Crew cost* comprise salaries for two flight crew plus one cabin staff for each forty passengers. Cabin staff cost, in the program, is considered as a continuous function with PAX but in fact would be a step function. This approximation is not regarded as significant in total cost estimation and avoids discontinuities in the optimising functions.

$$COSTC = \left(\frac{JCW + 1500\,(NPAS-40)}{CUTL}\right) TBLOC$$

CUTL is the crew utilisation per year, taken to be 800 hours in this program
JCW is the cost of two flight crew per year and is a fixed input value.

3.2 *Fuel and oil cost* are evaluated as:-

$$COSTF = \left[\frac{JPFUEL\,(MFUEL \times 9.81)}{INSTAG}\right] + (JOIL \times TBLOC)$$

where:-

JPFUEL is the price of fuel (per Newton) set as a fixed input value in the study, at a price equivalent to 75c per US gal.

MFUEL is the mass of fuel used for the mission (including 100 lb per stage for ground allowance)

INSTAGE is the number of stages in the mission

JOIL is the cost of oil burnt per hour (set at $2.00)

TBLOC is the block time (per stage)

3.3 *Landing fees* vary between different locations but are frequently related to aircraft size:-

COSLF = JCLF (MLAND x 9.81)

JCLF is the cost coefficient for landing fees. A fixed input value (set in this program to zero).

C9.4 COST PARAMETERS

The program evaluates several cost parameters:-

DOC per flight ($):-

DOCPF = COSTSC + COSTM+ COSTC + COSTF + COSTLF

DOC per mile ($):-

DOCPM = DOCPF ÷ (STAGE x 0.00054)

Seat mile cost (cents):-

SMC = (DOCPM ÷NPAS) x 100

These parameters were validated against detailed Short Brothers output and with Trevett's [22] analysis updated from 1984.

C10 Output Format

For each optimum aircraft nine pages of detailed output are produced (specimen output is shown in appendix F).

The output may be considered in three separate sections

(i) input data
(ii) aircraft design details
(iii) optimiser parameters.

(i) *The input section* lists all the design variables and constraints in their normalised (scale) form together with the optimiser model parameters (controls) and the initial (starting) point for the search.

(ii) The *aircraft design description* of the optimised (final) point includes:-

(a) geometric details of the configuration
(b) detailed component mass statement with the c.g. position and design load factors.
(c) aerodynamic data including the aircraft component drag breakdown, lift/drag polar, stability data and flap aerodynamics.
(d) mission analysis including climb, cruise and decent performance and total fuel useage.
(e) field performance including T.O., Landing and WAT analysis.
(f) detailed cost estimation including aircraft price and DOC.

The aircraft values are quoted in SI and Imperial units (note, the program evaluates solely in SI units).

(iii) *Optimum output parameters* show the final design point, the nature of the constraints, the derivatives of the variable and constants, the convergence criteria and any warning messages.

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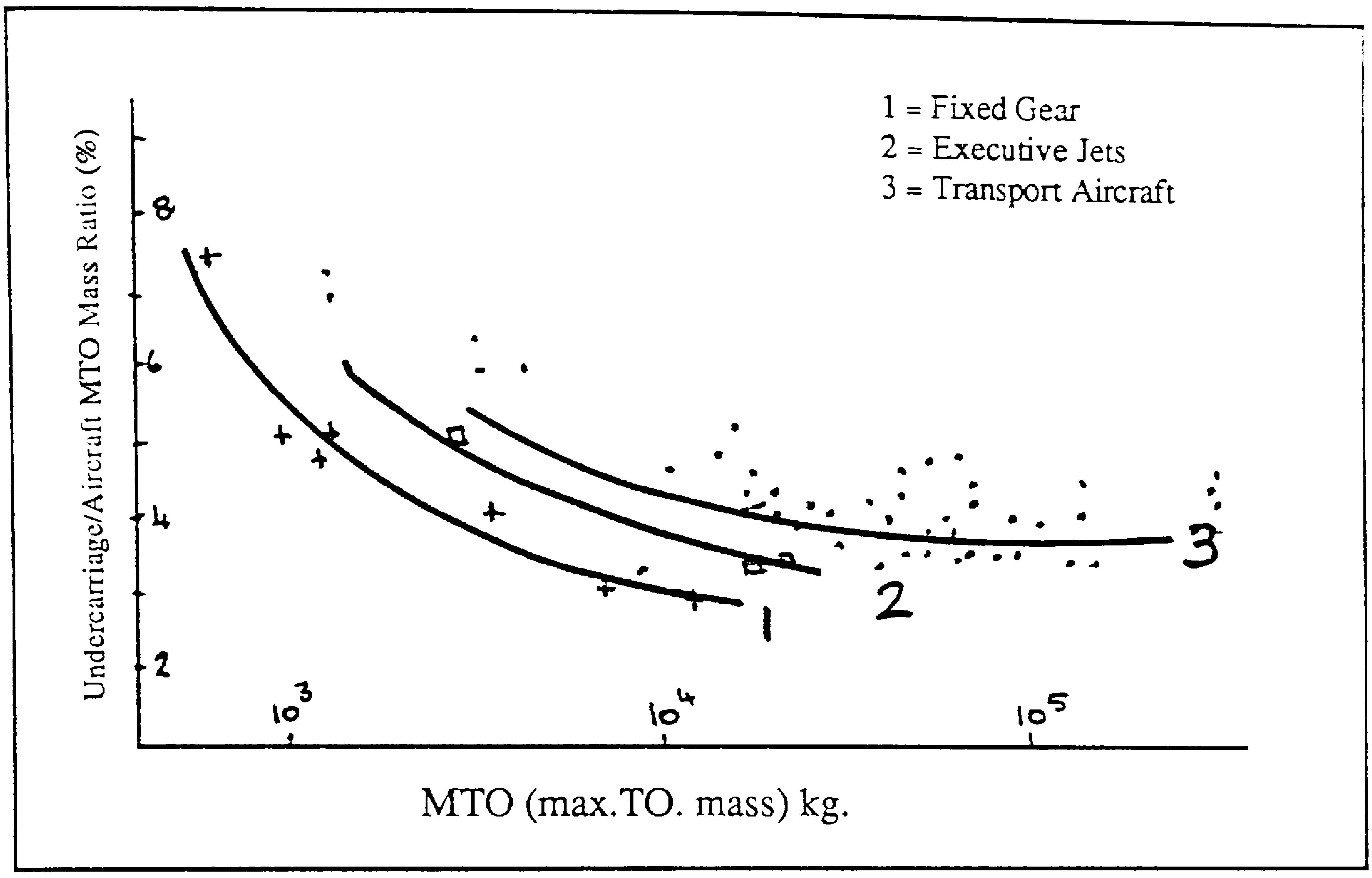

Figure C1 Undercarriage Mass Fraction (ref 9, Torenbeek)

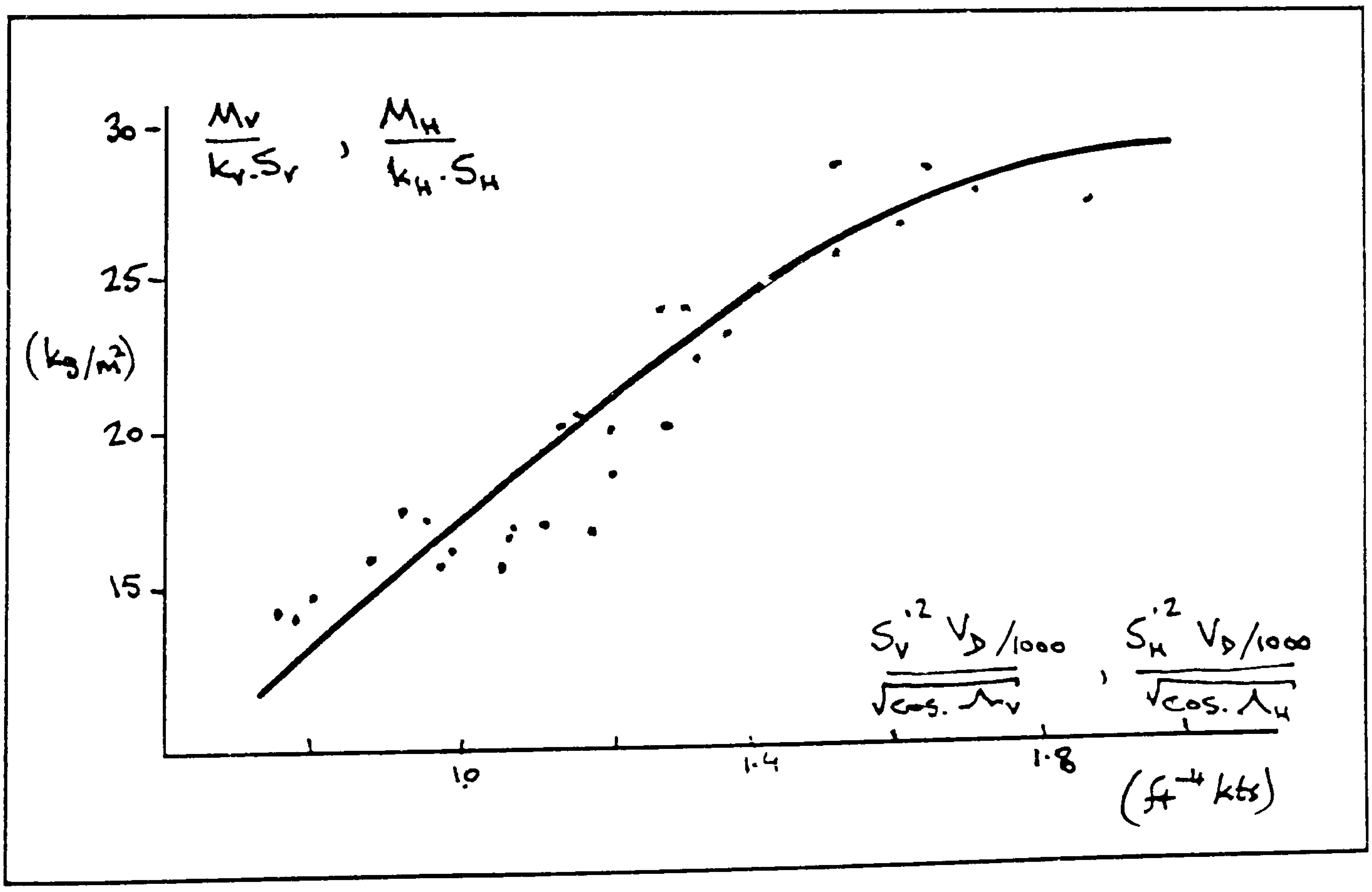

Figure C2 Tail-unit Mass Estimate (ref 9, Torenbeek)

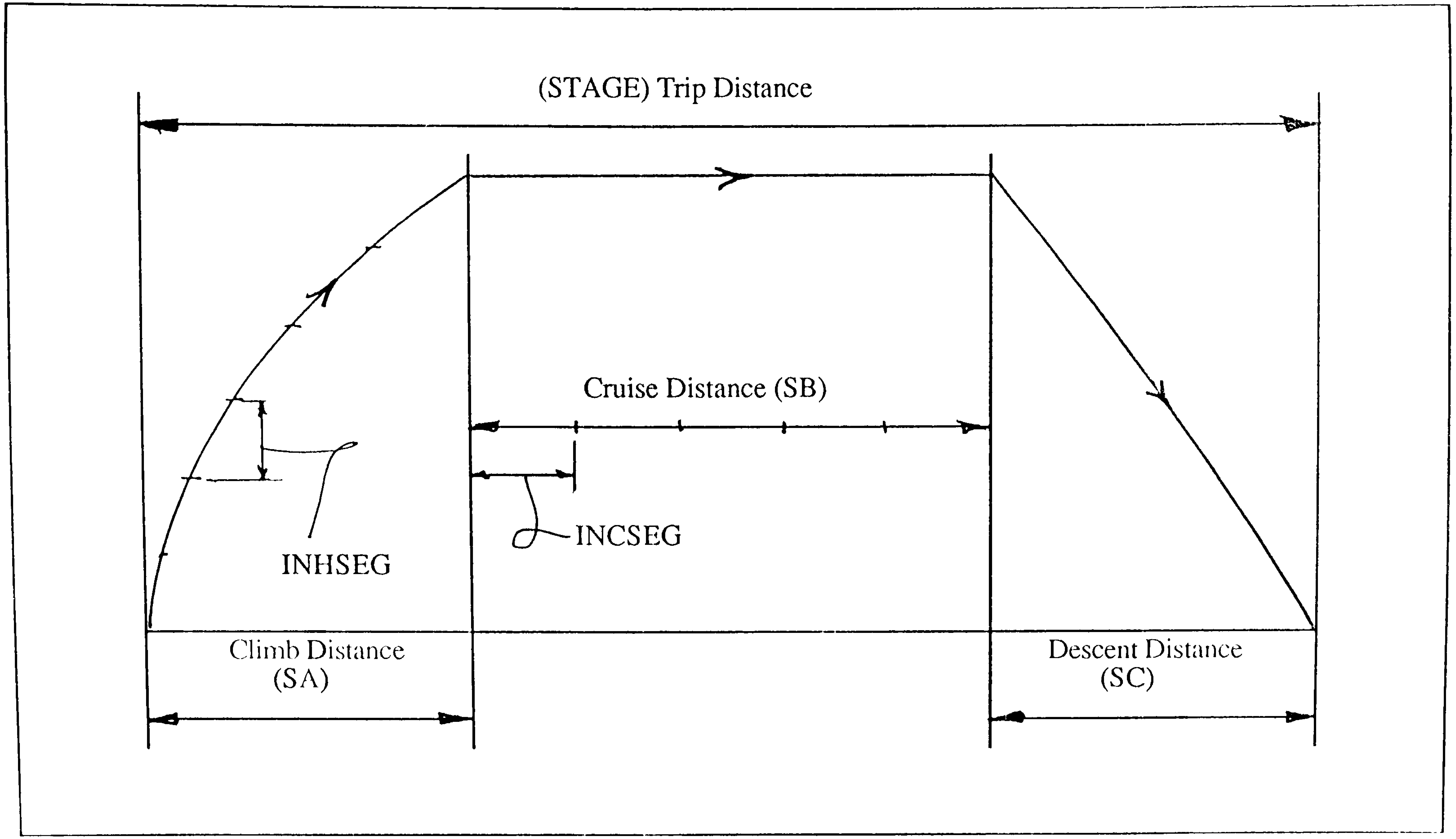

Figure C3. Flight Profile Descriptions

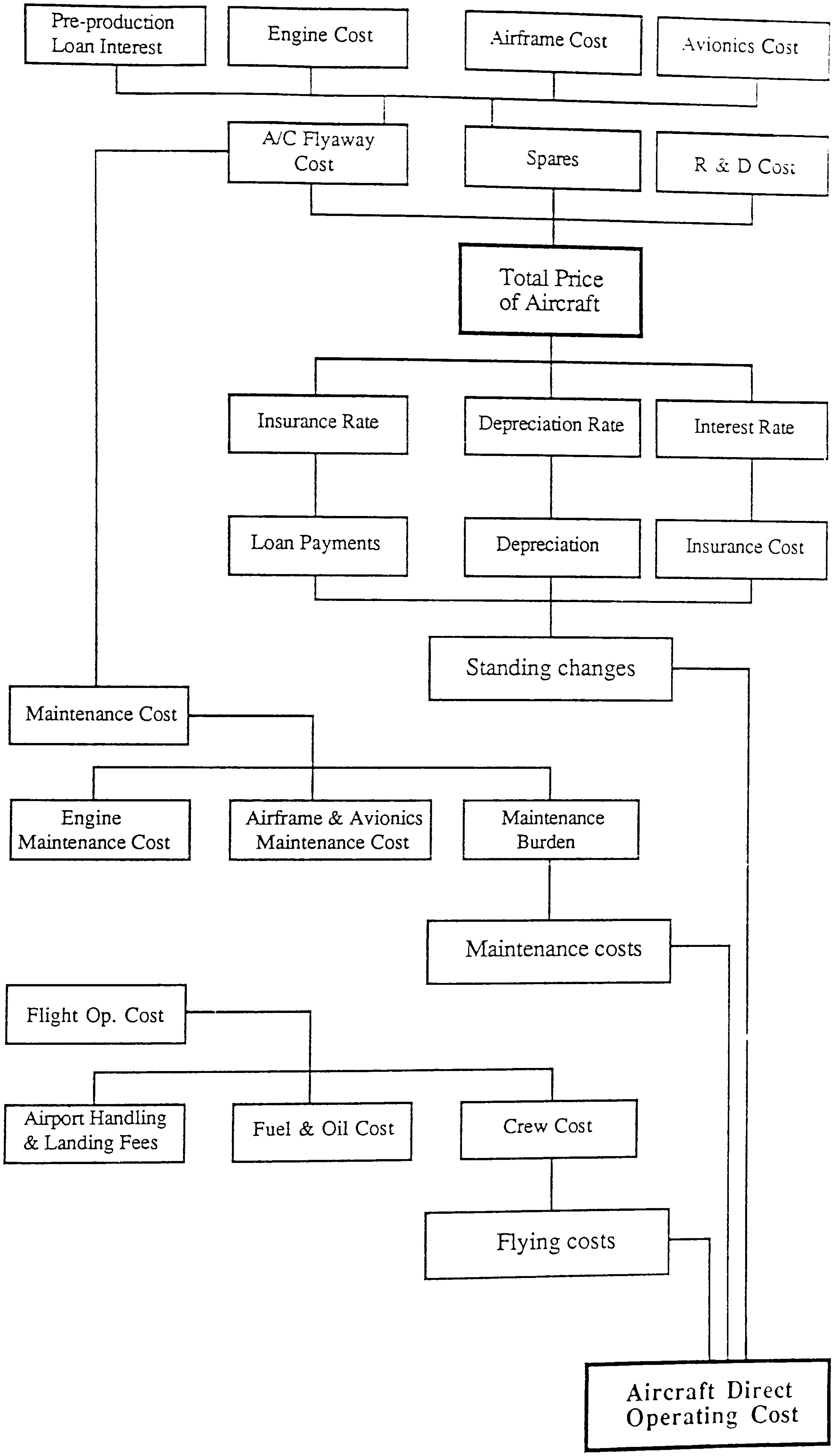

Figure C4 Cost Components in DOC Estimation.

APPENDIX D

This appendix contains the detailed results from the studies described in chapter 5. Details of each figure in this appendix is listed below:-

Initial Studies

FJX Developments

FJX.RR Stretch Study

Generalised Design Studies

Design	1	2	3	4		Units
Aspect Ratio	11.31	9.22	8.78	11.80		
Gross Wing Area	474.88	574.56	574.00	577.33		sq. ft
Empty Weight	23743	24808		25403		lbs
O.E.W	24382	25448	24900	26042		lbs
M.T.O	37096	38438	39300	38833		lbs
Mass of Fuel	5128	5405	4700	5206		lbs
Cruise Height	34567	35220		35900		feet
Cruise Mach No	0.75	0.75	0.75	0.75		
Mission Fuel	3749	3957		3830		lbs
Block Time	7748	7890		7948		secs
A/C Price	9.121	9.436	8.5/10.0	9.612		M $
DOC/Flight	2154	2235		2252		$
DOC/mile	2.48	2.57	3.59	2.59		$
Seat Mile Cost	6.19	6.42	8.98	6.47		cents
Balanced Field Length	5300	5300	5270	5300		feet
Landing Field Length	5300	4660		4600		feet
WAT Gradient	0.024	0.024	0.024	0.024		

Figure D1. Initial Optimisations (40-seat Baseline Establishment)

Design	1	2	3	4	5	Units
Aspect Ratio	9.22	9.08	9.01	9.62	10.34	
Gross Wing Area	574.56	581.93	588.17	582.83	596.06	sq. ft
Empty Weight	24808	24998	25176	25522	26583	lbs
O.E.W	25448	25637	25815	26161	27223	lbs
M.T.O	38438	38650	38847	39073	40082	lbs
Mass of Fuel	5405	5428	5447	5326	5274	lbs
Cruise Height	35220	35274	35323	35273	35390	feet
Cruise Mach No	0.75	0.75	0.75	0.75	0.75	
Mission Fuel	3957	3974	3988	3887	3841	lbs
Block Time	7890	7899	7908	7916	7965	secs
A/C Price	9.436	9.492	9.545	9.647	9.962	M $
DOC/Flight	2235	2245	2254	2256	2297	$
DOC/mile	2.57	2.58	2.59	2.59	2.64	$
Seat Mile Cost	6.42	6.45	6.48	6.49	6.60	cents
Balanced Field Length	5300	5300	5300	5300	5300	feet
Landing Field Length	4660	4660	4600	4600	4600	feet
WAT Gradient	0.024	0.024	0.024	0.024	0.024	

Figure D2. Initial Wing Geometry Sensitivity Study (40-seat Baseline Design)

Aspect Ratio	9.0	10.5	10.0	9.5	8.5	8.0	7.50		UNITS
Gross Wing Area	580.87	579.33	578.40	577.57	617.19	666.52	729.65		sq. ft
Empty Weight	24733	25209	25078	24946	25103	25643	26303		lbs
O.E.W	25373	25849	25717	25585	25743	26283	26942		lbs
M.T.O	38425	38874	38769	38667	38879	39547	40266		lbs
Mass of Fuel	5467	5440	5467	5497	5551	5679	5739		lbs
Cruise Height	36000	35418	35350	35275	36000	36000	36000		feet
Cruise Mach No	0.77	0.77	0.77	0.77	0.76	0.75	0.66		
Mission Fuel	4003	4029	4042	4056	4058	4147	4157		lbs
Block Time	7832	7710	7709	7709	7938	8118	9179		secs
A/C Price	9.414	9.555	9.516	9.477	9.524	9.634	9.879		M $
DOC/Flight	2226	2220	2217	2214	2266	2331	2573		$
DOC/mile	2.56	2.55	2.55	2.55	2.61	2.68	2.96		$
Seat Mile Cost	6.40	6.38	6.37	6.37	6.51	6.70	7.40		cents
Balanced Field Length	5300	5020	5131	5257	5300	5300	5305		feet
Landing Field Length	4624	4660	4660	4660	4442	4235	4000		feet
WAT Gradient	0.024	0.024	0.024	0.024	0.024	0.024	0.024		

Figure D3. Aspect Ratio Sensitivity Study **[Stage=1000sm., BFL=5300ft., LFL=4660ft., WAT=+25C/ISA/SL]**

Design Mission (stages nm.)	d(i) 1 x 1000	d(ii) 1 x 1000	a(i) 4 x 200	a(ii) 4 x 200	b(i) 3 x 250	b(ii) 3 x 250	c(i) 2 x 400	c(ii) 2 x 400	Units
Aspect Ratio	9.00	11.86	9.00	13.00	9.00	13.00	9.00	13.00	sq. ft
Gross Wing Area	580.87	482.04	733.05	485.03	661.91	477.46	613.16	462.32	lbs
Empty Weight	24733	24168	27273	24263	26124	24220	25312	239.02	lbs
O.E.W	25373	24808	27913	24904	26763	24860	25952	24541	lbs
M.T.O	38425	37708	42208	38674	40504	38268	39289	37710	lbs
Mass of Fuel	5467	5316	6710	6184	6155	5823	5752	5584	lbs
Cruise Height	36000	36000	26716	29366	32763	29029	35000	31744	feet
Cruise Mach No	0.77	0.79	0.51	0.72	0.74	0.77	0.76	0.78	
Mission Fuel	4003	3944	5234	4829	4672	4471	4283	4233	lbs
Block Time	7833	7493	2739	2112	2697	2393	3939	3627	secs
A/C Price	9.414	9.247	10.166	9.275	9.826	9.262	9.586	9.168	M $
DOC/Flight	2226	2188	940	760	943	847	1248	1156	$
DOC/mile	2.56	2.45	4.70	3.80	3.77	3.89	3.12	2.89	$
Seat Mile Cost	6.40	6.13	11.75	9.10	9.43	8.47	7.80	7.23	cents
Balanced Field Length	5300	5300	5334	5367	5300	5300	5300	5300	feet
Landing Field Length	4624	5300	4029	5248	4205	5300	4310	5231	feet
WAT Gradient	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	

Figure D4. Mission Sensitivity Study

Design	1		2	3	4	UNITS
Aspect Ratio	9.0		11.86	9.00	10.41	
Gross Wing Area	580.87		482.04	706.23	619.00	sq. ft
Empty Weight	24733		24168	27521	26726	lbs
O.E.W	25373		24808	28161	27366	lbs
M.T.O	38425		37708	41548	40548	lbs
Mass of Fuel	5467		5316	5802	5597	lbs
Cruise Height	36000		36000	36000	35453	feet
Cruise Mach No	0.77		0.79	0.73	0.76	
Mission Fuel	4003		3944	4241	4120	lbs
Block Time	7832		7493	8319	7888	secs
A/C Price	9.414		9.247	10.239	10.00	M $
DOC/Flight	2226		2188	2449	2310	$
DOC/mile	2.56		2.45	2.82	2.67	$
Seat Mile Cost	6.40		6.13	7.04	6.66	cents
Balanced Field Length	5300		5300	5300	5300	feet
Landing Field Length	4624		5300	4288	4660	feet
WAT Gradient	0.024		0.024	0.024	0.024	

Figure D5. Rear Engine Installation Study

	44 SEATS				48 SEATS				
Design	1	2	3	4	5	6	7	8	UNITS
Aspect Ratio	9.00	13.00	9.00	9.00	9.00	9.00	9.00	9.00	
Gross Wing Area	79903	532.50	568.83	517.88	744.78	632.23	569.12	561.55	sq.ft
Empty Weight	28534	25603	25909	25480	29179	27864	27254	27922	lbs
O.E.W	29191	26260	26566	26137	29854	28539	27925	28597	lbs
M.T.O	43484	39912	40553	40124	45085	43566	42907	43733	lbs
Mass of Fuel	5950	5308	5647	5643	6192	5925	5876	6034	lbs
Cruise Height	36000	36000	36000	35370	36000	36000	35554	34360	feet
Cruise Mach No	0.63	0.77	0.77	0.77	0.75	0.77	0.77	0.79	
Mission Fuel	4309	3906	4110	4098	4482	4309	4261	4406	lbs
Block Time	9711	7847	7746	7603	8083	7809	7654	7370	secs
A/C Price	10.545	9.677	9.957	9.924	10.931	10.636	10.551	10.885	M $
DOC/Flight	2812	2265	2320	2296	2566	2462	2422	2417	$
DOC/mile	3.23	2.60	2.67	2.64	2.95	2.89	2.79	2.78	$
Seat Mile Cost	7.35	5.92	6.06	6.00	6.15	5.95	5.80	5.79	cent
Balanced Field Length	5335	5300	5300	5300	5300	5300	5300	5300	feet
Landing Field Length	3938	5107	4928	5300	4293	4789	5169	5300	feet
WAT Gradient	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	

Figure D6 Baseline Aircraft Stretch Studies (44/48 seats)

Design	1	2	3	4	5	6	7		Units
Aspect Ratio	8.92	10.92	8.72	10.65	9.00	13.00	9.0		sq. ft
Gross Wing Area	566.44	467.94	562.55	464.71	568.78	470.78	580.87		lbs
Empty Weight	24007	22997	24072	23046	247.04	23977	24733		lbs
O.E.W	24646	23636	24712	23686	25343	24617	25373		lbs
M.T.O	37812	36481	37548	26214	38036	36885	38425		lbs
Mass of Fuel	5581	5260	5251	4943	5107	4683	5467		feet
Cruise Height	36000	36000	36000	36000	36000	36000	36000		
Cruise Mach No	0.62	0.63	0.62	0.65	0.62	0.62	0.77		
Wing Mass	3945	3456	4060	3552	4605	4357			lbs
Mission Fuel	4004	3750	3752	3517	3649	3331	4003		lbs
Block Time	9983	9736	9698	9209	9426	9453	7832		secs
A/C Price	9.199	8.899	9.218	8.915	9.405	9.190	9.414		M $
DOC/Flight	2625	2506	2543	2380	2502	2443	2226		$
DOC/mile	3.02	2.88	2.92	2.74	2.88	2.81	2.56		$
Seat Mile Cost	7.55	7.20	7.31	6.84	7.19	7.02	6.40		cents
Balanced Field Length	5300	5300	5300	5300	5300	4964	5300		feet
Landing Field Length	4660	5300	4660	5300	4660	5300	4624		feet
WAT Gradient	0.024	0.024	0.024	0.024	0.024	0.024	0.024		

Figure D7. Objective Function Sensitivity Study

Design	1	2	3	4	5	Units
Passengers	48	48	48	68	68	
Aspect Ratio	7.50	7.50	9.00	9.00	9.54	
Gross Wing Area	619.19	619.19	569.12	753.75	751.23	sq. ft
Empty Weight	31319	31319	27254	36438	36862	lbs
O.E.W	31994	31994	27925	37201	37625	lbs
M.T.O	48263	48263	42907	57913	58516	lbs
Mass of Fuel	7167	7167	5876	7817	7996	lbs
Cruise Height	35480	35480	35554	35901	35686	feet
Cruise Mach No	0.81	0.81	0.77	0.71	0.78	
Mission Fuel	5197	5197	4261	5656	5865	lbs
Block Time	7167	7167	7654	7703	7508	secs
A/C Price	12.375	12.375	10.551	13.917	14.043	M $
DOC/Flight	2705	2705	2422	3154	3135	$
DOC/mile	3.11	3.11	2.79	3.68	3.61	$
Seat Mile Cost	6.40	6.40	5.80	5.33	5.30	cents
Balanced Field Length	4557	4557	5300	5300	5300	feet
Landing Field Length	5300	5300	5169	5300	5300	feet
WAT Gradient	0.024	0.024	0.024	0.024	0.024	

Figure D8. Challenger Investigations

Design	1	2	3	4	5	6	7	8	9
Land. Field Length	5098.	5003.	4921.	4888.	4856.	4823.		5098.	ft.
Gross Wing Area	554.98	570.21	584.11	589.89	595.79	601.83		555.15	sq. ft
Fuselage Length	81.04	81.04	81.04	81.04	81.04	81.04		81.04	ft
Empty Weight	24616.14	24825.92	25018.63	25099.07	25181.52	25266.08		24634.79	lbs
O.E.M	25273.23	25483.01	25675.72	25756.16	25838.61	25923.17		25291.88	lbs
M.T.O.M	40348.49	40568.18	40772.12	40857.88	40946.12	41037.00		40366.01	lbs
TO Flap(Ang/Cl m)	19.11-2.22	19.29-2.23	19.29-2.23	19.29- 2.23	19.29-2.23	19.29-2.23		19.61-2.24	deg./
Landing Flap	40.00-2.56	40.00-2.56	40.00-2.56	40.00-2.56	40.00- 2.56	40.00-2.56		40.00-2.56	deg./
Cruise Mach No	0.76	0.76	0.76	0.76	0.76	0.75		0.76	
Cruise Speed	240.60	239.30	238.10	237.60	237.09	236.56		240.71	knots
Cruise Height	35761.85	35832.44	35889.64	35910.93	35931.62	35951.36		35751.41	ft
Stage Fuel	4679.36	4688.39	4698.41	4703.12	4708.23	4713.78		4679.98	lbs
Total Fuel	6273.61	6283.52	6294.75	6300.07	6305.85	6312.18		6272.47	lbs
Stage Time	8587.28	8630.93	8672.42	8690.09	8708.44	8727.49		8583.17	secs.
Stall Speed TO	98.40	97.16	96.20	95.81	95.42	95.03		98.00	knots
Stall Speed Landing	91.64	90.61	89.72	89.36	88.99	88.63		91.64	knots
WAT gradient	0.024	0.024	0.024	0.024	0.024	0.024		0.024	
BFL (Computed)	5098.36	5015.35	4953.11	4928.48	4904.00	4879.69		5070.75	ft
LFL (Computed)	5098.36	5003.22	4921.20	4888.39	4855.58	4822.78		5098.36	ft
A/C Price	7.48	7.55	7.60	7.63	7.65	7.68		7.49	$(m)
DOC/Flight	2286.36	2303.01	2318.81	2325.55	2332.54	2339.80		2286.37	$
DOC/mile	2.38	2.40	2.42	2.42	2.43	2.44		2.38	$
Seat Mile Cost	5.41	5.45	5.49	5.51	5.52	5.54		5.41	cents

Figure D9. **44 seat Designs - Effect of LFL requirement [AR = 9.27 , All designs]**

Design	1	2	3	4	5	6	7	8	Units
Aspect Ratio	9.27		9.27	9.27	9.27				
Gross Wing Area	554.98		562.14	570.66	575.64				sq. ft
Fuselage Length	81.04		81.04	81.04	81.04				ft
Engine Scale	1.00		1.05	1.10	1.15				
Empty Weight	24616.14		25096.80	25648.49	26009.02				lbs
O.E.M	25273.23		25753.89	26305.58	26666.11				lbs
M.T.O.M	40348.49		40908.42	41571.71	41963.34				lbs
TO Flap(Ang/Cl m)	19.11-2.22		19.29-2.23	19.29-2.23	19.29-2.23				deg./
Landing Flap	40.00-2.56		40.00-2.56	40.00-2.56	40.00-2.56				deg./
Cruise Mach No	0.76		0.78	0.79	0.79				
Cruise Speed	240.60		243.70	247.71	247.02				knots
Cruise Height	35761.85		35990.38	35990.38	35990.38				ft
Stage Fuel	4679.36		4746.16	4844.34	4865.32				lbs
Total Fuel	6273.61		6352.88	6464.48	6495.58				lbs
Stage Time	8587.28		8424.42	8269.68	8254.49				secs.
Stall Speed TO	98.40		98.26	98.26	98.26				knots
Stall Speed Landing	91.64		91.64	91.64	91.64				knots
WAT gradient	0.024		0.03	0.03	0.04				
BFL (Computed)	5098.36		4924.14	4786.78	4636.72				ft
LFL (Computed)	5098.36		5098.36	5098.36	5098.36				ft
A/C Price	9.38		9.62	9.88	10.08				$(m)
DOC/Flight	2470		2485	2507	2542				$
DOC/mile	2.57		2.59	2.61	2.65				$
Seat Mile Cost	5.85		5.88	5.93	6.02				cents

Figure D10. 44 seat Designs - Effect of CFE Engine Developments

Design	1	2	3	4	5	6	7	8	Units
Aspect Ratio	(Fixed) 9.27	(Fixed) 9.27	(Fixed) 9.27	(Fixed) 9.27	(Fixed) 9.27				
Gross Wing Area	554.98	557.59	528.05	535.97	539.43				sq. ft
Fuselage Length	81.04	81.04	81.04	81.04	81.04				ft
Engine Scale	1.00	1.00	1.05	1.10	1.15				
Empty Weight	24616.14	24716.95	24899.36	25447.95	25743.75				lbs
O.E.M	25273.23	25374.04	25556.45	26105.04	26400.84				lbs
M.T.O.M	40348.49	40442.87	40681.66	41336.94	41630.01				lbs
TO Flap(Ang/Cl m)	19.11-2.22	22.25-2.22	23.52-2.27	20.64-2.17	19.29-2.13				deg./
Landing Flap	40.00-2.56	40.00-2.70	40.00-2.71	40.00-2.71	40.00-2.71				deg./
Cruise Mach No	0.76	0.76	0.79	0.80	0.79				
Cruise Speed	240.60	238.79	246.40	249.94	248.10				knots
Cruise Height	35761.85	35990.38	35937.73	35990.38	35990.38				ft
Stage Fuel	4679.36	4662.69	4710.44	4803.59	4791.65				lbs
Total Fuel	6273.61	6267.18	6323.55	6430.24	6427.52				lbs
Stage Time	8587.28	8673.37	8339.46	8196.77	8214.25				secs.
Stall Speed TO	98.40	98.24	100.21	102.38	103.48				knots
Stall Speed Landing	91.64	89.06	91.64	91.64	91.64				knots
WAT gradient	0.024	0.024	0.03	0.03	0.04				
BFL (Computed)	5098.36	5098.36	5098.36	5098.36	5000.10				ft
LFL (Computed)	5098.36	4861.42	5098.36	5098.36	5098.36				ft
A/C Price	7.48	7.51	7.57	7.73	7.82				$(m)
DOC/Flight	2286.36	2303.77	2269.25	2286.81	2313.05				$
DOC/mile	2.38	2.40	2.36	2.38	2.41				$
Seat Mile Cost	5.41	5.45	5.37	5.41	5.48				cents

Figure D11. 44 seat Designs - Effect of Inproved Double Slotted Flaps (960nm., 5100ft.)

Design	1	2	3	4	5	6	7	8	9
Aspect Ratio (fixed)	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	
Gross Wing Area	929.48	784.67	603.20	606.72	938.69	865.91	612.51	570.08	sq. ft
Fuselage Length	92.91	92.91	92.91	92.91	92.91	92.91	92.91	92.91	ft
Engine Scale / Flap	1.0 / SSF	1.1 / SSF	1.2 / SSF	1.3 / SSF	1.0 / DSF	1.1 / DSF	1.2 / DSF	1.3 / DSF	
Empty Weight	32652.73	31430.30	29472.67	30730.43	32881.65	32742.62	29729.29	30476.89	lbs
O.E.M	33362.74	32140.31	30182.68	31440.44	33591.66	33452.63	30439.30	31186.90	lbs
M.T.O.M	51807.42	50911.80	48840.58	50214.10	51977.92	52373.89	49062.73	49960.65	lbs
TO Flap(Ang/Cl m)	7.17-1.75	12.60-1.96	18.38-2.18	19.29-2.22	7.33-1.71	11.77-1.87	20.88-2.16	22.84-2.23	deg./
Landing Flap	40.00-2.58	40.00-2.56	40.00-2.55	40.00-2.55	40.00-2.74	40.00-2.73	40.00- 2.69	40.00-2.70	deg./
Cruise Mach No	0.65	0.72	0.78	0.79	0.64	0.70	0.77	0.80	
Cruise Speed	202.44	225.60	243.46	252.55	202.03	219.29	240.56	256.33	knots
Cruise Height	35990.38	35990.38	35990.38	35372.57	35990.38	35990.38	35990.38	34900.91	ft
Stage Fuel	5735.29	5682.15	5588.61	5681.71	5741.56	5828.05	5547.30	5670.01	lbs
Total Fuel	7430.32	7569.39	7455.79	7571.56	7414.27	7735.10	7421.32	7571.65	lbs
Stage Time	10810.27	9775.89	8855.42	8568.49	10816.37	10139.14	8991.66	8504.30	secs.
Stall Speed TO	97.10	98.87	104.77	105.01	97.74	97.79	104.56	107.64	knots
Stall Speed Landing	79.83	86.50	96.91	97.89	77.19	80.85	93.75	97.89	knots
WAT gradient	0.024	0.024	0.024	0.03	0.024	0.024	0.024	0.03	
BFL (Computed)	6077.09	5698.75	5698.75	5459.65	6163.44	5722.72	5698.75	5698.75	ft
LFL (Computed)	4070.21	4633.72	5602.20	5698.75	3860.34	4153.96	5296.51	5698.75	ft
A/C Price	9.88	9.52	8.94	9.31	9.95	9.91	9.01	9.24	$(m)
DOC/Flight	3241.00	2993.37	2740.51	2765.14	3253.27	3143.78	2774.44	2740.52	$
DOC/mile	3.21	2.96	2.71	2.74	3.22	3.11	2.75	2.71	$
Seat Mile Cost	5.73	5.29	4.85	4.89	5.75	5.56	4.91	4.85	cents

Figure D12. 56 seat Designs - Scaled CFE engine (1010nm., 5700ft.)

Design	1	2	3	4	5	6	7	8	9
Aspect Ratio (Fix.)	Unfeasible Aircraft	9.27	9.27	9.27	Unfeasible Aircraft	Unfeasible Aircraft	9.27	9.27	
Gross Wing Area		847.93	672.15	652.86			691.58	595.41	sq. ft
Fuselage Length		106.36	106.36	106.36			106.36	106.36	ft
Eng.Scale / Flap		1.3 / SSF	1.4 / SSF	1.5 / SSF			1.4 / DSF	1.5 / DSF	
Empty Weight		37414.81	34956.46	36291.64			35447.83	34602.84	lbs
O.E.W		38177.74	35719.39	37054.57			36210.76	35365.77	lbs
M.T.O.W		60470.22	57864.64	59420.51			58356.80	57578.25	lbs
TO Flap(Ang/Cl m)		12.74-1.95	17.16-2.12	19.29-2.21			19.10-2.10	23.48-2.24	deg./
Landing Flap		40.00-2.53	40.00-2.54	40.00-2.54			40.00-2.69	40.00-2.69	deg./
Cruise Mach No		0.69	0.77	0.80			0.77	0.77	
Cruise Speed		216.57	243.54	261.07			241.28	251.79	knots
Cruise Height		35990.38	35571.81	34188.83			35878.48	34321.25	ft
Stage Fuel		6330.36	6394.24	6590.61			6387.45	6431.47	lbs
Total Fuel		8712.35	8542.69	8763.38			8543.48	8609.92	lbs
Stage Time		10226.81	9153.73	8683.88			9227.88	8946.44	secs.
Stall Speed TO		103.95	109.40	110.35			109.00	112.90	knots
Stall Speed Landing		91.14	100.03	102.81			96.28	103.10	knots
WAT gradient		0.024	0.024	0.03			0.024	0.024	
BFL (Computed)		6225.46	6200.71	6087.67			6200.71	6200.71	ft
LFL (Computed)		5051.94	5914.05	6200.71			5540.08	6230.10	ft
A/C Price		13.51	13.24	13.82			13.38	13.32	$(m)
DOC/Flight		3786	3504	3494			3542	3487	$
DOC/mile		3.75	3.37	3.36			3.41	3.35	$
Seat Mile Cost		6.69	4.95	4.94			5.01	4.93	cents

Figure D13. 68 seat Designs - Scaled CFE engines (1040nm., 6200ft.)

Design	1	2	3	4	5	6	7	8	9
Aspect Ratio (fixed)	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	
Gross Wing Area	554.98	601.83	557.59	575.64	539.43	585.13	6.34.15	547.72	sq. ft
Fuselage Length	81.04	81.04	81.04	81.04	81.04	81.04	81.04	81.04	ft
Engine Type / Flap	CFE / SSF	CFE / SSF	CFE / DSF	1.15CFE/SSF	1.15CFE/DSF	RR / SSF	RR / SSF	RR / DSF	
Empty Weight	24616	25266	24717	26009	25743	25962	26644	25567	lbs
O.E.M	25273	25923	25374	2666	26400	26619	27301	26225	lbs
M.T.O.M	40348	41037	40443	41963	41630	42618	43307	42229	lbs
TO Flap(Ang/Cl m)	19.11 / 2.22	19.29 / 2.23	22.25 / 2.22	19.29 / 2.23	19.29 / 2.13	19.29 / 2.23	19.29 / 2.23	19.29 / 2.13	deg./
Landing Flap	40.00 / 2.56	40.00 / 2.56	40.00 / 2.70	40.00 / 2.56	40.00 / 2.71	40.00 / 2.56	40.00 / 2.56	40.00 / 2.71	deg./
Cruise Mach No	0.76	0.75	0.76	0.79	0.79	0.85	0.85	0.85	
Cruise Speed	240.60	236.56	238.79	247.02	248.10	287.07	287.07	287.07	knots
Cruise Height	35762	35951	35990	35990	35990	32815	32815	32815	ft
							4956		
Stage Fuel	4679	4713	4663	4865	4791	4942	7204	4937	lbs
Total Fuel	6273	6312	6267	6495	6427	7197	7693	7202	lbs
Stage Time	8587	8727	8673	8254	8214	7683		7684	secs.
							95.04		
Stall Speed TO	98.40	95.03	98.24	98.26	103.48	98.26	88.63	103.48	knots
Stall Speed Landing	91.64	88.63	89.06	91.64	91.64	91.64		91.64	knots
							0.033		
WAT gradient	0.024	0.024	0.024	0.040	0.04	0.033	4483	0.040	
BFL (Computed)	5098	4879	5098	4636	5000	4681	4822	5050	ft
LFL (Computed)	5098	4822	4861	5098	5098	5098		5098	ft
							8.09		
A/C Price	7.48	7.68	7.51	7.90	7.82	7.88	2222	7.77	$(m)
DOC/Flight	2286	2339	2304	2338	2313	2195	2.31	2182	$
DOC/mile	2.38	2.44	2.40	2.44	2.41	2.29	5.26	2.27	$
Seat Mile Cost	5.41	5.54	5.45	5.54	5.48	5.20		5.17	cents

Figure D14 44 seat Designs with CFE & RR Engines [Stage = 960 nm., Field = 5100 ft.]

Design	1	2	3	4	5	6	7	8	9
Aspect Ratio (fixed)	9.27	9.27	9.27	9.27	9.27	9.27	9.27		
Gross Wing Area	603.20	606.72	612.51	570.08	708.66	594.30	599.10		sq. ft
Fuselage Length	92.91	92.91	92.91	92.91	92.91	92.91	92.91		ft
Engine Type / Flap	1.2CFE/SSF	1.3CFE/SSF	1.2CFE/DSF	1.3CFE/DSF	RR / SSF	1.1RR/SSF	1.2RR/SSF		
Empty Weight	29473	30730	29729	30476	30677	29707	30339		lbs
O.E.M	30182	31440	30439	31186	31387	30417	31049		lbs
M.T.O.M	4884	50214	49062	49960	50364	49098	49558		lbs
TO Flap(Ang/Cl m)	18.38 / 2.18	19.29 / 2.22	20.88 / 2.16	22.84 / 2.23	14.22 / 2.02	19.29 / 2.21	19.29 / 2.21		deg./
Landing Flap	40.00 / 2.55	40.00 / 2.55	40.00 / 2.69	40.00 / 2.70	40.00 / 2.56	40.00 / 2.55	40.00 / 2.55		deg./
Cruise Mach No	0.78	0.79	0.77	0.80	0.85	0.85	0.85		
Cruise Speed	243.46	252.55	240.56	256.33	289.40	287.37	287.07		knots
Cruise Height	35990	35372	35990	34900	32469	32770	32815		ft
Stage Fuel	5588	5681	5547	5670	5379	5158	5032		lbs
Total Fuel	7455	7571	7421	7571	7775	7478	7306		lbs
Stage Time	8855	8568	8992	8504	8206	8089	8055		secs.
Stall Speed TO	104.77	105.01	104.56	107.64	101.85	105.01	105.01		knots
Stall Speed Landing	96.91	97.89	93.75	97.89	90.58	97.89	97.89		knots
WAT gradient	0.024	0.030	0.024	0.030	0.024	0.030	0.040		
BFL (Computed)	5699	5459	5698	5698	5698	5472	5097		ft
LFL (Computed)	5602	5699	5296	5698	4999	5698	5698		ft
A/C Price	8.94	`9.31	9.01	9.24	9.30	9.01	9.20		$(m)
DOC/Flight	2740	2765	2774	2740	2564	2508	2535		$
DOC/mile	2.71	2.74	2.75	2.71	2.54	2.48	2.51		$
Seat Mile Cost	4.85	4.89	4.91	4.85	4.53	4.43	4.48		cents

Figure D15 56 seat Designs with CFE & RR Scaled Engines [Stage = 1010 nm., Field = 5700 ft.]

Design	1	2	3	4	5	6	7	8	9
Aspect Ratio (fixed)	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	
Gross Wing Area	672.15	652.86	691.58	595.41	664.14	639.03	626.53	631.45	sq. ft
Fuselage Length	106.36	106.36	106.36	106.36	106.36	106.36	106.36	106.36	ft
Engine Type / Flap	1.4CFE/SSF	1.5CFE/SSF	1.4CFE/DSF	1.5CFE/DSF	1.2RR?SSF	1.3RR/SSF	1.4RR/DSF	1.5RR/DSF	
Empty Weight	34956	36291	35447	34602	34609	34916	35254	35878	lbs
O.E.M	35719	37054	36211	35365	35372	35679	36017	36641	lbs
M.T.O.M	57864	59420	58356	57578	56862	58038	56949	57452	lbs
TO Flap(Ang/Cl m)	17.16 / 2.21	19.29 / 2.21	19.10 / 2.10	23.48 / 2.24	16.40 / 2.09	16.19 / 2.08	19.29 / 2.20	19.29 / 2.21	deg./
Landing Flap	40.00 / 2.54	40.00 / 2.54	40.00 / 2.69	40.00 / 2.69	40.00 / 2.54	40.00 / 2.54	40.00 / 2.54	40.00 / 2.54	deg./
Cruise Mach No	0.77	0.80	0.77	0.77	0.85	0.85	0.85	0.85	
Cruise Speed	243.54	261.07	241.28	251.79	306.28	396.19	287.07	287.07	knots
Cruise Height	35571	34188	35878	34321	30005	18126	32815	32815	ft
Stage Fuel	6494	6590	6387	6431	5513	6426	5052	4968	lbs
Total Fuel	8542	8763	8543	8609	7887	8756	7329	7208	lbs
Stage Time	9153	8683	9227	8946	8254	7719	8304	8319	secs.
Stall Speed TO	109.40	110.35	109.00	112.90	109.89	113.46	110.35	110.35	knots
Stall Speed Landing	100.03	102.81	96.28	103.10	99.77	102.81	102.81	102.81	knots
WAT gradient	0.024	0.030	0.024	0.024	0.024	0.030	0.040	0.040	
BFL (Computed)	6200	6087	6200	6200	6200	6200	5481	5193	ft
LFL (Computed)	5914	6200	5540	6230	5887	6200	6200	6200	ft
A/C Price	10.58	10.97	10.72	10.47	10.48	10.57	10.67	10.85	$(m)
DOC/Flight	3230	3216	3267	3201	2839	2853	2877	2922	$
DOC/mile	3.11	3.09	3.14	3.08	2.73	2.74	2.77	2.81	$
Seat Mile Cost	4.57	4.55	4.62	4.53	4.02	4.03	4.07	4.13	cents

Figure D16. 68 seat Designs with CFE & RR Scaled Engines [Stage = 1040nm., Field = 6200 ft.]

	Design	1	2	3	4	5	6	7	8	9	10	11	12
Aspect Ratio		9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27
Gross Wing Area	sq. ft	579.12	632.84	697.22	814.44	548.93	597.47	652.86	731.47	522.85	567.53	617.02	676.62
Fuselage Length	ft	92.91	92.91	92.91	92.91	92.91	92.91	92.91	92.91	92.91	92.91	92.91	92.91
Empty Weight	lbs	28316.64	29162.35	30160.41	31924.24	27914.31	28687.91	29557.77	30764.03	27567.98	28288.62	29074.33	30000.43
O.E.M	lbs	30616.90	31504.89	32552.86	34404.87	30194.45	31006.73	31920.08	33186.66	29830.80	30587.47	31412.47	32384.87
M.T.O.M	lbs	46844.91	48500.49	50316.99	53230.82	46433.26	48011.80	49673.27	51817.02	46083.14	47608.75	49172.75	50908.56
TO Flap(Ang/Cl m)	deg./	19.2-2.2	17.8-2.1	16.2-2.1	13.7-2.0	19.2-2.22	17.8-2.2	16.4-2.14	14.5-2.0	19.0-2.2	17.6-2.2	16.3-2.1	14.9-2.0
Landing Flap	deg./	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.6	40.0-2.52	40.0-2.5	40.0-2.6	40.0-2.5	40.0-2.52	40.0- 2.5	40.0-2.5	40.0-2.5
Cruise Mach No		0.77	0.76	0.75	0.72	0.77	0.77	0.76	0.74	0.78	0.77	0.76	0.75
Cruise Speed	knots	264.88	249.93	235.78	225.79	269.22	254.85	241.71	231.70	273.01	259.09	246.50	235.05
Cruise Height	ft	32048.37	34127.59	35752.46	35990.38	31503.39	33585.73	35233.21	35990.38	31006.64	33080.19	34754.96	35990.38
Stage Length nm.		608.	782.	956.	1130.	608.	782.	956.	1130.	608.	782.	956.	1130.
Stage Fuel	lbs	3368.53	4130.26	4884.08	5900.98	3377.37	4141.91	4881.48	5735.12	3387.13	4157.64	4892.44	5642.61
Total Fuel	lbs	5025.91	5793.49	6562.03	7624.00	5036.70	5802.96	6551.08	7428.25	5050.23	5819.18	6558.18	7321.58
Stage Time	secs.	5395.33	7026.57	8797.74	10783.89	5332.37	6923.38	8617.02	10445.90	5281.29	6842.56	8486.25	10253.17
Stall Speed TO	knots	103.95	102.36	100.67	98.05	106.51	104.96	103.36	101.37	108.98	107.45	105.91	104.25
Stall Speed Landing	knots	93.35	90.12	86.80	81.80	95.53	92.32	89.16	85.34	97.57	94.36	91.27	88.05
WAT gradient		0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
BFL (Computed)	ft	5698.75	5698.75	5698.75	5698.75	5898.88	5898.88	5898.88	5898.88	6099.01	6099.01	6099.01	6099.01
LFL (Computed)	ft	5258.75	4958.25	4659.95	4232.17	5467.21	5162.04	4870.84	4532.18	5667.66	5355.30	5064.11	4770.45
A/C Price	$(m)	11.16	11.42	11.73	12.28	11.03	11.27	11.54	11.92	10.92	11.15	11.39	11.68
DOC/Flight	$	1853.31	2340.73	2876.76	3543.62	1829.59	2303.03	2810.74	3390.10	1810.27	2273.64	2763.16	3299.59
DOC/mile	$	3.04	2.99	3.01	3.13	3.01	2.94	2.94	3.00	2.97	2.91	2.89	2.92
Seat Mile Cost	cents	5.44	5.34	5.37	5.60	5.37	5.25	5.25	5.36	5.31	5.19	5.16	5.21

Figure D17. Aircraft Stretch Studies (56 seats, RB580 engine)

Design		1	2	3	4	5	6	7	8	9	10	11	12
Aspect Ratio		9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27
Gross Wing Area	sq. ft	585.53	591.14	606.05	656.83	557.46	564.04	571.17	615.42	533.80	539.42	541.52	581.99
Fuselage Length	ft	92.91	92.91	92.91	92.91	92.91	92.91	92.91	92.91	92.91	92.91	92.91	92.91
Empty Weight	lbs	29211.14	29609.32	29537.20	30318.10	28611.21	29406.28	29070.82	29756.21	28772.93	29221.87	28677.91	29331.28
O.E.M	lbs	31556.13	31974.21	31898.48	32718.43	30926.20	31761.02	31408.78	32128.44	31096.00	31567.39	30996.23	31682.27
M.T.O.M	lbs	48041.53	49322.01	49791.79	51386.69	48439.01	49101.33	49307.16	50784.52	47570.96	48903.60	48905.91	50334.99
TO Flap(Ang/Cl m)	deg./	17.7-2.2	21.2-2.3	20.7-2.3	19.2-2.2	19.7-2.27	20.9-2.3	20.6-2.3	19.3-2.2	19.3-2.2	20.72.3	20.5-2.3	19.2-2.2
Landing Flap	deg./	40.0-2.6	40.0-2.6	40.0-2.6	40.0-2.6	40.1-2.57	40.0-2.5	40.0-2.5	40.0-2.6	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.5
Cruise Mach No		0.78	0.79	0.78	0.77	0.70	0.80	0.78	0.77	0.79	0.80	0.78	0.78
Cruise Speed	knots	281.38	276.06	251.57	242.08	326.33	280.24	255.65	246.19	289.35	284.12	259.21	249.09
Cruise Height	ft	30140.38	31303.36	34602.66	35990.38	18126.42	30986.75	33970.12	35376.35	29488.16	30690.25	33412.51	34922.85
Stage Length	nm.	608.	782.	956.	1130.	608.	782.	956.	1130.	608.	782.	956.	1130.
Stage Fuel	lbs	3603.11	4460.80	5005.44	5783.91	4387.53	4449.59	5010.07	5775.51	3584.63	4440.16	5018.54	5760.88
Total Fuel	lbs	5283.30	6145.69	6691.20	7465.34	6309.69	6138.20	6696.28	7453.23	5272.85	6134.11	6707.58	7450.61
Stage Time	secs.	5156.59	6548.10	8274.34	9890.33	5542.50	6477.97	8198.48	9787.94	5053.62	6415.43	8136.26	9710.04
Stall Speed TO	knots	106.06	103.90	103.47	102.11	107.46	106.42	106.22	104.93	109.18	108.87	108.87	107.59
Stall Speed Landing	knots	93.77	93.77	92.53	89.60	95.84	95.85	94.90	92.06	97.89	97.89	97.11	94.30
WAT gradient		0.03	0.024	0.024	0.024	0.03	0.024	0.024	0.024	0.03	0.024	0.024	0.024
BFL (Computed)	ft	5298.49	5298.49	5298.49	5297.85	5500.61	5498.62	5498.62	5498.13	5560.16	5698.75	5698.75	5698.75
LFL (Computed)	ft	5298.49	5298.49	5181.53	4910.18	5497.97	5498.62	5406.77	5137.32	5698.75	5698.75	5622.28	5349.14
A/C Price	$(m)	11.66	11.78	11 76	12.00	11.47	11.72	11.61	11.82	11.52	11.66	11.49	11.69
DOC/Flight	$	1875.16	2315.23	2787.01	3295.03	2040.25	2291.10	2752.34	3245.29	1837.85	2269.63	2724.25	3206.91
DOC/mile	$	3.08	2.96	2.91	2.91	3.35	2.93	2.88	2.87	3.02	2.90	2.85	2.84
Seat Mile Cost	cents	5.50	5.28	5.20	5.21	5.99	5.23	5.14	5.13	5.39	5.18	5.09	5.07

Figure D18 (sheet 1) Aircraft Stretch Studies (56 seats, Near-term engine)

Design		13	14	15	16								
Aspect Ratio		9.27	9.27	9.27	9.27								
Gross Wing Area	sq. ft	514.52	516.06	515.95	553.10								
Fuselage Length	ft	92.91	92.91	92.91	92.91								
Empty Weight	lbs	28903.08	28977.27	28342.71	28948.89								
O.E.M	lbs	31232.66	31310.56	30644.27	31280.76								
M.T.O.M	lbs	47658.05	48645.48	48570.01	49948.46								
TO Flap(Ang/Cl m)	deg./	19.3-2.2	20.4-2.2	20.3-2.2	19.1-2.2								
Landing Flap	deg./	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.5								
Cruise Mach No		0.80	0.80	0.78	0.78								
Cruise Speed	knots	289.34	287.08	262.39	252.64								
Cruise Height	ft	29993.16	30452.47	32913.07	34365.43								
Stage Length		608.	782.	956.	1130.								
nm.Stage Fuel	lbs	3538.19	4433.02	5030.05	5774.04								
Total Fuel	lbs	5240.60	6132.82	6723.64	7465.59								
Stage Time	secs.	4985.20	6368.56	8083.58	9638.02								
Stall Speed TO	knots	111.36	111.36	111.43	110.16								
Stall Speed Landing	knots	99.91	99.88	99.19	96.39								
WAT gradient		0.03	0.024	0.024	0.024								
BFL (Computed)	ft	5768.02	5898.88	5898.88	5898.88								
LFL (Computed)	ft	5901.54	5898.88	5829.18	5550.91								
A/C Price	$(m)	11.56	11.58	11.39	11.57								
DOC/Flight	$	1819.60	2250.45	2701.01	3175.14								
DOC/mile	$	2.99	2.88	2.82	2.81								
Seat Mile Cost	cents	5.34	5.13	5.04	5.02								

Figure D18 (sheet 2) Aircraft Stretch Studies (56 seats, Near-term engine)

Design		1	2	3	4	5	6	7	8	9	10	11	12
Aspect Ratio		9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27
Gross Wing Area	sq. ft	604.07	607.65	611.01	642.48	624.19	646.89	689.78	737.49	696.01	746.47	751.94	774.92
Fuselage Length	ft	106.36	106.36	106.36	106.36	109.64	109.64	109.64	109.64	112.93	112.93	112.93	112.93
Seats/PAX		68	68	68	68	72	72	72	72	76	76	76	76
Empty Weight	lbs	35521.81	35818.42	35296.77	35694.65	36331.94	36411.33	37136.08	37956.04	38031.43	38840.15	38552.14	38799.97
O.E.M	lbs	38237.89	38549.34	38001.60	38419.38	39107.05	39190.41	39951.40	40812.36	40910.04	41759.19	41456.78	41717.00
M.T.O.M	lbs	59780.39	60962.00	61053.36	62320.56	61557.58	62438.78	64073.99	65775.10	64263.38	66052.69	66150.00	67191.24
TO Flap(Ang/Cl m)	deg./	20.7-2.3	24.0-2.4	23.9-2.4	22.9-2.3	23.4-2.3	22.7-2.3	21.5-2.3	20.3-2.2	21.3-2.3	20.1-2.2	19.8-2.2	19.0-2.2
Landing Flap	deg./	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.54	40.0-2.5	40.0-2.5
Cruise Mach No		0.80	0.80	0.78	0.78	0.79	0.78	0.77	0.77	0.78	0.78	0.71	0.68
Cruise Speed	knots	286.50	279.03	262.36	253.95	278.37	263.32	254.37	244.92	265.28	255.90	222.98	211.67
Cruise Height	ft	30274.62	31662.38	33195.45	34215.57	30994.52	32697.31	34017.73	35425.70	32417.45	33791.85	35990.38	35990.38
Stage Length	nm.	956.	1130.	1304.	1478.	956.	1130.	1304.	1478.	956.	1130.	1304.	1478.
Stage Fuel	lbs	5972.61	6834.15	7496.97	8340.24	6045.64	6834.83	7699.77	8527.19	6073.02	7006.72	7350.51	8186.24
Total Fuel	lbs	7939.94	8810.11	9448.53	10298.19	8046.95	8845.20	9719.66	10560.04	8150.49	9090.61	9490.36	10301.96
Stage Time	secs.	7690.57	9088.22	10806.26	12387.90	7850.85	9476.84	11034.16	12642.46	8087.55	9648.62	12334.23	14584.92
Stall Speed TO	knots	113.84	111.91	111.84	110.88	111.47	110.80	109.59	108.35	109.45	108.15	108.08	108.05
Stall Speed Landing	knots	101.84	101.84	101.06	98.89	101.83	100.08	97.49	94.93	98.64	95.85	95.32	94.05
WAT gradient		0.03	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
BFL (Computed)	ft	6099.01	6099.01	6098.72	6098.79	6099.61	6098.80	6098.89	6099.01	6099.01	6098.98	6099.01	6168.81
LFL (Computed)	ft	6099.01	6099.01	6018.97	5798.56	6098.17	5918.72	5659.82	5410.02	5774.01	5498.64	5447.62	5325.17
A/C Price	$(m)	13.96	14.05	13.89	14.01	14.21	14.24	14.46	14.72	14.75	15.00	14.91	14.99
DOC/Flight	$	3131.23	3635.77	4173.90	4736.02	3231.14	3791.88	4373.09	4978.78	3382.01	3984.87	4812.89	5594.48
DOC/mile	$	3.27	3.22	3.20	3.20	3.38	3.35	3.35	3.37	3.54	3.53	3.69	3.78
Seat Mile Cost	cents	4.81	4.73	4.71	4.71	4.69	4.66	4.66	4.68	4.65	4.64	4.86	4.98

Figure D19 (sheet 1) Aircraft Stretch Studies (Far-term engine, 6100ft. Field)

Design		13	14	15	16								
Aspect Ratio		9.27	9.27	9.27	9.27								
Gross Wing Area	sq. ft	753.95	779.17	797.25	819.52								
Fuselage Length	ft	116.21	116.21	116.21	116.21								
Seats/PAX		80	80	80	80								
Empty Weight	lbs	39438.48	39825.98	39968.71	40155.50								
O.E.M	lbs	42405.96	42812.84	42962.70	43158.83								
M.T.O.M	lbs	66187.63	67355.47	68355.09	69365.70								
TO Flap(Ang/Cl m)	deg./	19.7-2.2	18.8-2.2	18.4-2.2	17.7-2.1								
Landing Flap	deg./	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.5								
Cruise Mach No		0.72	0.67	0.67	0.65								
Cruise Speed	knots	225.64	208.55	208.69	203.47								
Cruise Height	ft	35990.38	35990.38	35990.38	35990.38								
Stage Length	nm.	956.	1130.	1304.	1478.								
Stage Fuel	lbs	5612.54	6441.43	7355.95	8246.92								
Total Fuel	lbs	7780.76	8574.36	9460.08	10311.72								
Stage Time	secs.	9086.02	11361.45	13089.43	15095.31								
Stall Speed TO	knots	108.08	108.04	108.03	108.02								
Stall Speed Landing	knots	96.65	95.29	94.37	93.15								
WAT gradient		0.024	0.024	0.024	0.024								
BFL (Computed)	ft	6101.56	6179.84	6251.43	6324.19								
LFL (Computed)	ft	5576.86	5444.60	5355.85	5239.41								
A/C Price	$(m)	15.19	15.31	15.35	15.41								
DOC/Flight	$	3702.01	4506.57	5146.17	5872.91								
DOC/mile	$	3.87	3.99	3.95	3.97								
Seat Mile Cost	cents	4.84	4.98	4.93	4.97								

Figure D19 (sheet 2) Aircraft Stretch Studies (Far-term engine, 6100ft. Field)

	Design	17	18	19	20	21	22	23	24	25	26	27	28
Aspect Ratio			9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27	9.27
Gross Wing Area	sq. ft		582.00	590.10	620.51	600.00	622.38	658.06	701.87	663.26	709.59	728.87	744.76
Fuselage Length	ft		106.36	106.36	106.36	109.64	109.64	109.64	109.64	112.93	112.93	112.93	112.93
Seats/PAX			68	68	68	72	72	72	72	76	76	76	76
Empty Weight	lbs		35435.28	35186.75	35599.67	36124.52	36200.75	36700.08	37460.93	37544.02	38344.58	38456.31	38499.38
O.E.M	lbs		38147.03	37886.08	38319.65	38889.26	38969.30	39493.60	40292.49	40398.25	41238.85	41356.16	41401.38
M.T.O.M	lbs		60582.42	60952.97	62222.43	61321.57	62229.86	63641.20	65279.70	63788.70	65517.66	66150.00	66805.94
TO Flap(Ang/Cl m)	deg./		23.6-2.3	23.5-2.3	22.5-2.4	23.2-2.3	22.4-2.3	21.4-2.3	20.2-2.2	21.2-2.3	20.0-2.2	19.4-2.2	18.9-2.2
Landing Flap	deg./		40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.5	40.0-2.5
Cruise Mach No			0.80	0.79	0.78	0.79	0.78	0.78	0.77	0.78	0.78	0.76	0.68
Cruise Speed	knots		283.85	266.20	257.00	279.62	267.04	257.90	248.85	270.09	258.70	237.04	211.50
Cruise Height	ft		30680.54	32834.46	33956.99	30909.92	32279.66	33467.90	34810.47	31680.13	33354.20	35990.38	35990.38
Stage Length	nm.		1130.	1304.	1478.	956.	1130.	1304.	1478.	956.	1130.	1304.	1478.
Stage Fuel	lbs		6854.23	7506.66	8324.79	5999.18	6842.56	7723.78	8553.29	6114.08	6992.74	7484.06	8111.36
Total Fuel	lbs		8832.83	9463.64	10300.22	8029.60	8857.39	9744.67	10584.50	8187.28	9075.95	9590.98	10226.59
Stage Time	secs.		9049.90	10712.45	12283.30	7813.66	9401.39	10963.55	12548.64	8026.32	9583.51	11547.61	14536.84
Stall Speed TO	knots		114.41	114.05	113.08	113.77	113.07	112.00	110.79	111.89	110.61	110.15	110.06
Stall Speed Landing	knots		103.75	102.78	100.59	103.75	101.89	99.49	96.94	100.69	97.96	96.75	95.73
WAT gradient			0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
BFL (Computed)	ft		6299.14	6298.86	6299.14	6299.14	6298.94	6299.02	6299.14	6299.00	6299.14	6299.14	6337.55
LFL (Computed)	ft		6299.14	6196.98	5970.88	6299.14	6104.95	5859.36	5605.70	5981.75	5706.11	5586.89	5486.83
A/C Price	$(m)		13.93	13.85	13.98	14.15	14.17	14.33	14.56	14.60	14.84	14.88	14.89
DOC/Flight	$		3611.92	4143.51	4699.70	3207.88	3762.37	4334.73	4927.81	3351.07	3943.05	4588.75	5553.26
DOC/mile	$		3.20	3.18	3.18	3.35	3.33	3.32	3.33	3.50	3.49	3.52	3.76
Seat Mile Cost	cents		4.70	4.67	4.68	4.66	4.62	4.62	4.63	4.61	4.59	4.63	4.94

Figure D19 (sheet 3) Aircraft Stretch Studies (Far-term engine, 6300ft. Field)

Design		29	30	31	32								
Aspect Ratio			9.27	9.27	9.27								
Gross Wing Area	sq. ft		747.14	768.61	796.63								
Fuselage Length	ft		116.21	116.21	116.21								
Seats/PAX			80	80	80								
Empty Weight	lbs		39293.20	39637.83	40031.07								
O.E.M	lbs		42253.41	42615.28	43028.18								
M.T.O.M	lbs		66854.33	68012.84	69160.61								
TO Flap(Ang/Cl m)	deg./		18.8-2.2	18.4-2.2	17.1-2.1								
Landing Flap	deg./		40.0-2.5	40.0-2.5	40.0-2.5								
Cruise Mach No			0.70	0.69	0.65								
Cruise Speed	knots		219.86	215.26	204.28								
Cruise Height	ft		35990.38	35990.38	35990.38								
Stage Length	nm.		1130.	1304.	1478.								
Stage Fuel	lbs		6479.35	7337.59	8154.56								
Total Fuel	lbs		8627.91	9452.09	10221.17								
Stage Time	secs.		10875.90	12669.78	14906.52								
Stall Speed TO	knots		110.06	109.92	109.92								
Stall Speed Landing	knots		96.97	95.94	94.31								
WAT gradient			0.024	0.024	0.024								
BFL (Computed)	ft		6340.96	6413.25	6497.62								
LFL (Computed)	ft		5608.25	5507.77	5350.45								
A/C Price	$(m)		15.14	15.25	15.37								
DOC/Flight	$		4337.71	4997.96	5796.76								
DOC/mile	$		3.84	3.83	3.92								
Seat Mile Cost	cents		4.80	4.79	4.90								

Figure D19 (sheet 4) Aircraft Stretch Studies (Far-term engine, 6300ft. Field)

	Design	1	2	3	4	5	6	7	8	9	10	11	12
Aspect Ratio		8.80	9.00	9.20	9.40	9.60	9.80	10.00	10.20	10.40	10.60	10.80	11.00
Gross Wing Area	sq. ft	660.58	648.07	636.68	626.21	616.86	608.05	599.70	592.20	585.28	578.89	573.03	567.66
Fuselage Length	ft	92.91	92.91	92.91	92.91	92.91	92.91	92.91	92.91	92.91	92.91	92.91	92.91
Empty Weight	lbs	29418.73	29302.79	29198.06	29102.10	29018.69	28946.30	28884.09	28832.63	28787.27	28747.56	28713.74	28685.37
O.E.M	lbs	31774.09	31652.36	31542.39	31441.63	31354.05	31278.04	31212.72	31158.69	31111.05	31069.36	31033.85	31004.06
M.T.O.M	lbs	48815.41	48673.06	48544.91	48427.12	48326.96	48238.84	48161.35	48098.82	48043.18	47993.82	47951.35	47915.15
TO Flap(Ang/Cl m)	deg./	16.1-2.1	16.9-2.1	17.6-2.2	18.3-2.2	18.9-2.2	19.5-2.2	20.2-2.3	20.9-2.3	21.5-2.3	22.1-2.3	22.7-2.3	23.3-2.3
Landing Flap	deg./	40.0-2.6	40.0-2.5	40.0-2.6	40.0-2.6	40.0-2.6	40.0-2.6	40.0-2.6	40.0-2.6	40.0-2.6	40.0-2.6	40.0-2.6	40.0-2.6
Cruise Mach No		0.76	0.76	0.76	0.76	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.78
Cruise Speed	knots	246.41	248.04	249.49	250.78	252.06	253.22	254.28	255.35	256.32	257.22	258.06	258.84
Cruise Height	ft	34372.86	34270.94	34166.14	34060.61	33961.43	33860.36	33757.72	33661.01	33567.18	33476.42	33389.77	33307.24
Stage Fuel	lbs	4151.47	4141.77	4133.67	4126.26	4122.56	4118.89	4114.76	4113.84	4113.05	4112.28	4111.87	4111.76
Total Fuel	lbs	5839.21	5818.60	5800.41	5783.38	5770.80	5758.70	5746.52	5738.03	5730.02	5722.36	5715.39	5708.99
Stage Time	secs.	7117.03	7074.08	7037.29	7005.85	6975.53	6948.87	6925.57	6902.41	6881.80	6863.43	6846.72	6831.49
Stall Speed TO	knots	102.06	102.20	102.32	102.43	102.52	102.61	102.68	102.74	102.79	102.84	102.88	102.91
Stall Speed Landing	knots	88.52	89.24	89.90	90.52	91.08	91.64	92.21	92.73	93.22	93.69	94.12	94.53
WAT gradient		0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
BFL (Computed)	ft	5698.75	5698.75	5698.75	5698.75	5698.75	5698.75	5698.75	5698.75	5698.75	5698.75	5698.75	5698.75
LFL (Computed)	ft	4813.32	4877.41	4937.59	4994.37	5046.19	5098.29	5151.15	5200.18	5246.71	5290.79	5332.29	5371.29
A/C Price	$(m)	11.50	11.46	11.43	11.40	11.37	11.35	11.33	11.32	11.30	11.29	11.28	11.27
DOC/Flight	$	2372.48	2357.61	2344.75	2333.53	2323.41	2314.51	2306.67	2299.58	2293.30	2287.72	2282.76	2278.34
DOC/mile	$	3.03	3.01	3.00	2.98	2.97	2.96	2.95	2.94	2.93	2.92	2.92	2.91
Seat Mile Cost	cents	5.41	5.38	5.35	5.32	5.30	5.28	5.26	5.25	5.23	5.22	5.21	5.20

Figure D20. Aspect Ratio Sensitivity Study (56 seats, 782 nm., 5700 ft.)

Design		1	2	3	4	5	6	7	8	9
Aspect Ratio		9.30	9.30	9.30	9.30	9.30	9.30	9.30	9.30	9.30
Gross Wing Area	sq. ft	581.70	546.53	515.68	591.77	555.96	524.58	601.54	601.53	536.45
Fuselage Length	ft	99.47	99.47	99.47	99.47	99.47	99.47	99.47	99.47	99.47
Engine Scale		1.262	1.263	1.264	1.324	1.324	1.326	1.386	1.386	1.382
Empty Weight	lbs	32502.	32214.	31977.	33316.	33030.	32798.	34100.	36971.	33572.
O.E.M	lbs	35030.	34728.	34479.	35884.	35584.	35341.	36708.	39722.	36154.
M.T.O.M	lbs	54896.	54572.	54315.	56966.	56645.	56401.	58997.	61740.	58429.
TO Flap(Ang/Cl m)	deg./	24.0- 2.4	23.5- 2.4	23.1- 2.3	24.8- 2.4	24.3- 2.4	23.9- 2.4	25.5- 2.4	23.3- 2.4	24.5- 2.4
Landing Flap	deg./	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5
Cruise Mach No		0.79	0.79	0.80	0.79	0.79	0.80	0.79	0.73	0.80
Cruise Speed	knots	272.04	276.88	281.33	265.09	269.96	274.62	260.12	253.32	269.32
Cruise Height	ft	31838.99	31381.05	30972.95	33025.76	32556.95	32115.77	33871.55	31719.26	32971.82
Stage Length	nm.	1000.	1000.	1000.	1250.	1250.	1250.	1500.	1500.	1500.
Stage Fuel	lbs	5912.10	5885.05	5867.14	7103.17	7076.72	7065.54	8287.82	7908.34	8260.07
Total Fuel	lbs	7863.17	7842.42	7833.73	9079.20	9058.98	9056.94	10287.51	10015.61	10272.84
Stage Time	secs.	8250.09	8160.16	8078.62	10275.27	10163.46	10059.60	12300.18	12956.93	12055.26
Stall Speed TO	knots	108.45	111.99	115.45	108.93	112.47	115.94	109.40	113.45	116.21
Stall Speed Landing	knots	98.90	101.84	104.68	98.90	101.84	104.68	98.90	101.84	104.34
WAT gradient		0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.072	0.024
BFL (Computed)	ft	5800.	6099.	6398.	5800.	6099.	6398.	5800.	4637.	6398.
LFL (Computed)	ft	5800.	6099.	6398.	5800.	6099.	6398.	5800.	6099.	6361.
A/C Price	$(m)	12.81	12.72	12.65	13.15	13.06	12.99	13.47	15.16	13.30
DOC/Flight	$	3073.27	3036.44	3005.50	3801.12	3755.96	3718.17	4550.98	5213.43	4452.26
DOC/mile	$	3.07	3.04	3.01	3.04	3.00	2.97	3.03	3.48	2.97
Seat Mile Cost	cents	5.12	5.06	5.01	5.07	5.01	4.96	5.06	5.79	4.95

Figure D21. Generalised Design Studies (60 seat aircraft)

Design		1	2	3	4	5	6	7	8	9
Aspect Ratio		9.30	9.30	9.30	9.30	9.30	9.30	9.30	9.30	9.30
Gross Wing Area	sq. ft	669.12	629.05	593.27	680.29	639.20	602.96	691.28	648.83	603.75
Fuselage Length	ft	106.04	106.04	106.04	106.04	106.04	106.04	106.04	106.04	106.04
Engine Scale		1.430	1.431	1.432	1.498	1.498	1.499	1.565	1.563	1.565
Empty Weight	lbs	37037.	36724.	36433.	37900.	37600.	37325.	38755.	38398.	38135.
O.E.M	lbs	39848.	39519.	39213.	40754.	40438.	40150.	41652.	41276.	41000.
M.T.O.M	lbs	62819.	62484.	62161.	65078.	64731.	64430.	67295.	66883.	66593.
TO Flap(Ang/Cl m)	deg./	24.2- 2.4	23.8- 2.4	23.4- 2.3	24.9- 2.4	24.5- 2.4	24.1- 2.4	25.7- 2.4	25.3- 2.4	25.4- 2.4
Landing Flap	deg./	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5
Cruise Mach No		0.78	0.79	0.79	0.78	0.79	0.80	0.78	0.79	0.80
Cruise Speed	knots	275.23	278.95	283.70	266.61	272.08	277.03	261.65	266.76	272.79
Cruise Height	ft	31163.65	30841.25	30394.25	32520.66	32008.75	31538.65	33367.74	32857.89	32277.93
Stage Length	nm.	1000.	1000.	1000.	1250.	1250.	1250.	1500.	1500.	1500.
Stage Fuel	lbs	6488.79	6427.63	6402.90	7766.28	7730.48	7710.65	9061.52	9021.44	8995.84
Total Fuel	lbs	8566.85	8562.37	8545.08	9921.52	9889.73	9877.35	11240.32	11203.99	11189.72
Stage Time	secs.	8256.63	8174.22	8090.16	10310.26	10184.40	10076.01	12343.91	12207.27	12047.68
Stall Speed TO	knots	108.02	111.52	114.95	108.49	112.00	115.43	108.96	112.47	116.35
Stall Speed Landing	knots	98.88	101.84	104.68	98.90	101.84	104.68	98.90	101.84	105.41
WAT gradient		0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
BFL (Computed)	ft	5802.	6099.	6398.	5800.	6099.	6398.	5800.	6099.	6398.
LFL (Computed)	ft	5798.	6099.	6398.	5800.	6099.	6398.	5800.	6099.	6475.
A/C Price	$(m)	14.46	14.37	14.28	14.82	14.73	14.64	15.17	15.06	15.00
DOC/Flight	$	3431.14	3389.00	3351.58	4246.72	4191.89	4146.11	5084.27	5018.76	4963.35
DOC/mile	$	3.43	3.39	3.35	3.40	3.35	3.32	3.39	3.35	3.31
Seat Mile Cost	cents	4.77	4.71	4.65	4.72	4.66	4.61	4.71	4.65	4.60

Figure D22. Generalised Design Studies (72 seat aircraft)

Design		1	2	3	4	5	6	7	8	9
Aspect Ratio		9.30	9.30	9.30	9.30	9.30	9.30	9.30	9.30	9.30
Gross Wing Area	sq. ft	737.61	690.25	651.43	746.64	701.48	661.20	759.17	712.35	671.41
Fuselage Length	ft	112.60	112.60	112.60	112.60	112.60	112.60	112.60	112.60	112.60
Engine Scale		1.563	1.557	1.558	1.629	1.628	1.628	1.701	1.699	1.699
Empty Weight	lbs	40828.	40240.	39972.	41542.	41181.	40850.	42496.	42087.	41758.
O.E.M	lbs	43865.	43247.	42966.	44614.	44236.	43888.	45616.	45187.	44841.
M.T.O.M	lbs	69021.	68358.	68057.	71162.	70759.	70390.	73583.	73109.	72745.
TO Flap(Ang/Cl m)	deg./	24.3- 2.4	23.9- 2.4	23.5- 2.3	25.0- 2.4	24.6- 2.4	24.3- 2.4	25.7- 2.4	25.3- 2.4	25.0- 2.4
Landing Flap	deg./	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5
Cruise Mach No		0.78	0.79	0.79	0.78	0.79	0.79	0.78	0.79	0.79
Cruise Speed	knots	275.67	279.78	285.12	268.99	272.96	277.98	262.78	268.04	273.09
Cruise Height	ft	31024.35	30523.29	30041.85	32046.52	31689.23	31200.44	33060.02	32529.18	32033.49
Stage Length	nm.	1000.	1000.	1000.	1250.	1250.	1250.	1500.	1500.	1500.
Stage Fuel	lbs	6887.16	6840.95	6814.21	8308.47	8228.81	8201.46	9652.05	9604.83	9579.98
Total Fuel	lbs	9152.83	9107.98	9087.61	10543.74	10519.93	10498.84	11963.72	11918.99	11900.50
Stage Time	secs.	8261.60	8194.72	8098.80	10313.06	10210.01	10102.35	12362.13	12223.91	12094.60
Stall Speed TO	knots	107.75	111.26	114.67	108.26	111.74	115.16	108.70	112.20	115.63
Stall Speed Landing	knots	98.90	101.84	104.68	98.88	101.84	104.68	98.90	101.84	104.68
WAT gradient		0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
BFL (Computed)	ft	5800.	6099.	6398.	5802.	6099.	6398.	5800.	6099.	6398.
LFL (Computed)	ft	5800.	6099.	6398.	5799.	6099.	6398.	5800.	6099.	6398.
A/C Price	$(m)	15.83	15.64	15.56	16.14	16.02	15.92	16.53	16.40	16.30
DOC/Flight	$	3708.01	3657.71	3615.49	4583.39	4524.80	4472.73	5489.63	5416.14	5354.19
DOC/mile	$	3.71	3.66	3.62	3.67	3.62	3.58	3.66	3.61	3.57
Seat Mile Cost	cents	4.64	4.57	4.52	4.58	4.52	4.47	4.57	4.51	4.46

Figure D23. Generalised Design Studies (80 seat aircraft)

Design		1	2	3	4	5	6	7	8	9
Aspect Ratio		9.30	9.30	9.30	9.30	9.30	9.30	9.30	9.30	9.30
Gross Wing Area	sq. ft	637.45	599.06	565.37	647.53	608.51	574.26	656.54	617.59	579.86
Fuselage Length	ft	106.04	106.04	106.04	106.04	106.04	106.04	106.04	106.04	106.04
Engine Scale		1.369	1.369	1.371	1.433	1.433	1.435	1.495	1.497	1.505
Empty Weight	lbs	36195.	35877.	35617.	37056.	36742.	36485.	37808.	37567.	37318.
O.E.M	lbs	37108.	36790.	36530.	37969.	37655.	37398.	38721.	38480.	38231.
M.T.O.M	lbs	59837.	59493.	59226.	61979.	61644.	61384.	63999.	63747.	63497.
TO Flap(Ang/Cl m)	deg./	24.0- 2.4	23.6- 2.3	23.2- 2.3	24.8- 2.4	24.4- 2.4	24.0- 2.4	25.6- 2.4	25.2- 2.4	25.0- 2.4
Landing Flap	deg./	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5
Cruise Mach No		0.79	0.80	0.80	0.79	0.80	0.80	0.79	0.80	0.81
Cruise Speed	knots	274.70	279.49	284.14	267.82	272.79	277.51	262.47	268.03	273.13
Cruise Height	ft	31624.00	31180.62	30755.36	32811.92	32338.87	31897.55	33667.16	33160.61	32677.84
Stage Length	nm.	1000.	1000.	1000.	1250.	1250.	1250.	1500.	1500.	1500.
Stage Fuel	lbs	6264.37	6232.22	6214.87	7522.72	7494.88	7481.90	8768.31	8750.40	8737.70
Total Fuel	lbs	8325.96	8300.56	8292.90	9607.76	9586.63	9583.39	10875.39	10864.33	10863.04
Stage Time	secs.	8203.12	8114.63	8031.69	10213.54	10101.45	9998.03	12240.29	12086.16	11951.95
Stall Speed TO	knots	108.22	111.74	115.19	108.69	112.22	115.67	109.17	112.69	116.32
Stall Speed Landing	knots	98.90	101.84	104.68	98.90	101.84	104.68	98.90	101.84	104.96
WAT gradient		0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
BFL (Computed)	ft	5800.	6099.	6398.	5800.	6099.	6398.	5800.	6099.	6398.
LFL (Computed)	ft	5800.	6099.	6398.	5800.	6099.	6398.	5800.	6099.	6427.
A/C Price	$(m)	13.57	13.47	13.40	13.91	13.82	13.74	14.21	14.15	14.08
DOC/Flight	$	3276.44	3237.14	3203.97	4048.14	4000.03	3959.59	4841.50	4783.99	4736.04
DOC/mile	$	3.28	3.24	3.20	3.24	3.20	3.17	3.23	3.19	3.16
Seat Mile Cost	cents	4.55	4.50	4.45	4.50	4.44	4.40	4.48	4.43	4.39

Figure D24. Reduced Weight [-5% OEW] Studies (72 seat aircraft)

Design		1	2	3	4	5	6	7	8	9	10	11	12
Aspect Ratio		9.30	9.30	9.30	9.30	9.30	9.30	9.30	9.30	9.30	9.30	9.30	9.30
Gross Wing Area	sq. ft	713.22	681.48	653.62	628.42	718.96	688.75	662.02	637.28	726.10	696.18	668.81	644.29
Fuselage Length	ft	112.60	112.60	112.60	112.60	112.60	112.60	112.60	112.60	112.60	112.60	112.60	112.60
Engine Scale		1.503	1.497	1.493	1.490	1.548	1.545	1.546	1.546	1.595	1.594	1.594	1.596
Empty Weight	lbs	39989.	39487.	39135.	38851.	40438.	40117.	39905.	39701.	41003.	40738.	40506.	40362.
O.E.M	lbs	42984.	42457.	42087.	41789.	43455.	43118.	42896.	42682.	44048.	43770.	43527.	43376.
M.T.O.M	lbs	66882.	66328.	65903.	65551.	68346.	67986.	67744.	67520.	69926.	69623.	69359.	69203.
TO Flap(Ang/Cl m)	deg./	23.5- 2.4	23.2- 2.3	22.9- 2.3	22.7- 2.3	24.0- 2.4	23.8- 2.4	23.5- 2.3	23.3- 2.3	24.6- 2.4	24.3- 2.4	24.0- 2.4	23.8- 2.4
Landing Flap	deg./	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5
Cruise Mach No		0.79	0.79	0.79	0.79	0.78	0.79	0.79	0.79	0.78	0.79	0.79	0.79
Cruise Speed	knots	287.42	289.28	289.56	289.56	278.46	281.62	284.97	288.15	272.51	276.04	279.26	282.93
Cruise Height	ft	29331.11	29022.30	29037.81	29120.05	30600.01	30254.60	29945.95	29646.50	31520.15	31168.54	30859.42	30536.44
Stage Length	nm.	783.	783.	783.	783.	957.	957.	957.	957.	1130.	1130.	1130.	1130.
Stage Fuel	lbs	5650.01	5622.06	5561.90	5501.83	6627.02	6601.38	6578.60	6562.70	7597.00	7570.33	7545.40	7535.08
Total Fuel	lbs	7894.29	7867.84	7812.29	7758.60	8888.27	8864.13	8845.28	8834.74	9874.68	9850.01	9828.97	9824.11
Stage Time	secs.	6446.24	6425.21	6409.60	6394.30	7888.21	7836.17	7778.84	7726.33	9314.61	9244.90	9180.83	9107.36
Stall Speed TO	knots	108.48	110.83	113.12	115.38	108.84	111.17	113.47	115.74	109.18	111.51	113.81	116.07
Stall Speed Landing	knots	99.88	101.84	103.75	105.64	99.88	101.84	103.75	105.64	99.88	101.84	103.75	105.64
WAT gradient		0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
BFL (Computed)	ft	5899.	6099.	6299.	6499.	5899.	6099.	6299.	6499.	5899.	6099.	6299.	6499.
LFL (Computed)	ft	5899.	6099.	6299.	6499.	5899.	6099.	6299.	6499.	5899.	6099.	6299.	6499.
A/C Price	$(m)	15.49	15.32	15.21	15.12	15.69	15.58	15.52	15.46	15.93	15.84	15.77	15.73
DOC/Flight	$	2948.92	2922.40	2899.05	2878.36	3540.69	3509.27	3481.42	3456.42	4143.69	4107.18	4074.52	4045.25
DOC/mile	$	3.77	3.73	3.70	3.68	3.70	3.67	3.64	3.61	3.67	3.63	3.60	3.58
Seat Mile Cost	cents	4.71	4.67	4.63	4.60	4.63	4.59	4.55	4.52	4.58	4.54	4.51	4.47

Figure D25. (sheet 1)   80-Seat Aircraft Design Studies

Design		13	14	15	16	17	18	19	20
Aspect Ratio		9.30	9.30	9.30	9.30	9.30	9.30	9.30	9.30
Gross Wing Area	sq. ft	734.14	703.88	676.21	648.82	742.02	711.41	683.44	657.76
Fuselage Length	ft	112.60	112.60	112.60	112.60	112.60	112.60	112.60	112.60
Engine Scale		1.645	1.644	1.643	1.627	1.694	1.693	1.693	1.694
Empty Weight	lbs	41645.	41382.	41152.	40783.	42273.	42009.	41781.	41583.
O.E.M	lbs	44723.	44446.	44205.	43817.	45382.	45105.	44866.	44657.
M.T.O.M	lbs	71582.	71278.	71017.	70245.	73210.	72906.	72652.	72439.
TO Flap(Ang/Cl m)	deg./	25.1- 2.4	24.8- 2.4	24.5- 2.4	24.1- 2.4	25.5- 2.4	25.3- 2.4	25.0- 2.4	24.8- 2.4
Landing Flap	deg./	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5
Cruise Mach No		0.78	0.79	0.79	0.79	0.78	0.79	0.79	0.80
Cruise Speed	knots	268.41	271.89	275.16	266.79	264.91	268.40	271.82	275.16
Cruise Height	ft	32224.44	31878.38	31562.56	32678.61	32817.13	32467.45	32129.65	31804.85
Stage Length	nm.	1304.	1304.	1304.	1304.	1478.	1478.	1478.	1478.
Stage Fuel	lbs	8561.93	8532.79	8508.80	8143.89	9514.21	9485.16	9466.63	9456.85
Total Fuel	lbs	10831.40	10804.44	10784.04	10401.26	15966.72	11770.40	11755.98	11778.30
Stage Time	secs.	10726.	10646.	10572.	10691.	11798.	12049.	11962.	11879.
Stall Speed TO	knots	109.51	111.84	114.14	116.30	109.83	112.16	114.47	116.74
Stall Speed Landing	knots	99.88	101.84	103.75	105.63	99.88	101.84	103.75	105.64
WAT gradient		0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
BFL (Computed)	ft	5899.	6099.	6299.	6500.	5899.	6099.	6299.	6499.
LFL (Computed)	ft	5899.	6099.	6299.	6498.	5899.	6099.	6299.	6499.
A/C Price	$(m)	16.19	16.11	16.04	15.90	16.45	16.37	16.30	16.24
DOC/Flight	$	4758.21	4716.46	4679.15	4650.75	5384.78	5337.63	5295.57	5257.96
DOC/mile	$	3.65	3.62	3.59	3.57	3.64	3.61	3.58	3.56
Seat Mile Cost	cents	4.56	4.52	4.48	4.46	4.55	4.51	4.48	4.45

Figure D25. (sheet 2) 80-Seat Aircraft Design Studies

Design		1	2	3	4								
Aspect Ratio		9.30	9.70	10.20	10.70								
Gross Wing Area	sq. ft	639.20	636.93	635.10	633.62								
Fuselage Length	ft	106.04	106.04	106.04	106.04								
Engine Scale		1.498	1.477	1.454	1.435								
Empty Weight	lbs	37600.	37445.	37334.	37248.								
O.E.M	lbs	40438.	40276.	40159.	40068.								
M.T.O.M	lbs	64731.	64503.	64316.	64164.								
TO Flap(Ang/Cl m)	deg./	24.5- 2.4	25.2- 2.4	26.1- 2.4	26.9- 2.5								
Landing Flap	deg./	40.0- 2.5	40.0- 2.5	40.0- 2.5	40.0- 2.5								
Cruise Mach No		0.79	0.79	0.78	0.78								
Cruise Speed	knots	272.08	270.67	269.39	268.30								
Cruise Height	ft	32008.75	32060.12	32114.72	32154.09								
Stage Fuel	lbs	7730.48	7688.38	7644.14	7607.63								
Total Fuel	lbs	9889.73	9824.27	9753.66	9693.30								
Stage Time	secs.	10184.40	10230.07	10272.01	10309.27								
Stall Speed TO	knots	112.00	111.50	110.93	110.42								
Stall Speed Landing	knots	101.84	101.84	101.84	101.84								
WAT gradient		0.024	0.024	0.024	0.024								
BFL (Computed)	ft	6099.	6099.	6099.	6099.								
LFL (Computed)	ft	6099.	6099.	6099.	6099.								
A/C Price	$(m)	14.73	14.65	14.59	14.53								
DOC/Flight	$	4191.89	4183.34	4174.73	4168.11								
DOC/mile	$	3.35	3.35	3.34	3.33								
Seat Mile Cost	cents	4.66	4.65	4.64	4.63								

Figure D26. Aspect Ratio Sensitivity Studies (72 seats, 1250 nm., 6100 ft.)

APPENDIX E

This appendix contains a partial listing of the synthesis program described in chapter 4 and appendix C. A full listing may be obtained from the author on request to Loughborough Unviersity.

```
*************************************************************************
*                                                                       *
*          Turbo-fan Commuter Aircraft Optimisation                     *
*                    Issue 3  October 1989                              *
*                                                                       *
*                     Lloyd Ross Jenkinson                              *
*                                                                       *
*    This program is based on the RAE optimiser (RQPMIN) and            *
*    earlier studies concerned with turbo-prop short-haul               *
*    aircraft done in association with D Simos (1983-86). The           *
*    introduction of the fan-engine data, modification of the           *
*    aircraft synthesis model and the development of the                *
*    PERI-OPT output option were undertaken in conjuction with          *
*    Q R Ali (1986-88). This version of the program unifies             *
*    the previous work, tidies-up the code and adds more                *
*    descriptions to the text. Changes required by the Unix             *
*    operating system and associated graphics software are              *
*    also introduced to allow the program to be run on the              *
*    new university Hewlett Packard HP9000 mainframe computer.          *
*                                                                       *
*         (c) copywrite LOUGHBOROUGH UNIVERSITY  1989                   *
*                                                                       *
*************************************************************************
      PROGRAM orj
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)

$include "rqp.incl.f"
$include "input.incl.f"
$include "orj.incl.f"

*******************************************************************
*  This is the executive segment calling the input data files,   *
*  the aircraft fixed data file and the aircraft synthesis file *
*******************************************************************


      DOUBLE PRECISION MFB, MSTAR


*   Calculate constants used in the program
      PII   = 22.0d0/7.0d0
      zero  = 0.0d0
      onep  = 1.0d0
      onen  = -1.0d0
      two   = 2.0d0
      one80 = 180.0
      Tatm  = 288.16d0
      VoG   = 9.81d0
      iterol= 0

* =========================================
* Choose the single-pass or optimiser option
* =========================================
```

```
      call coua('single-pass or optimiser version (S or O)?')
      READ 1,SO

*    This segment deals with the single pass option
*    ------------------------------------------------
1     FORMAT (A)
      IF (SO.EQ.'S'.or. SO .eq. 's') THEN
         CALL DATAIN
         CALL INPUT
          DO 100 I = 1, 50
            XVALIN(I) = XSCALE(I) * XDATUM(I)
100       CONTINUE
         CALL SUB1
         CALL USERF(XVALIN,DUMMY1,IOCODE,1,3,0)

*    This segment calls the optimiser files
*    --------------------------------------
      ELSEIF (SO.EQ.'O'.or. SO .eq. 'o') THEN
          CALL DATAIN
          CALL RQPMIN
      ENDIF

      END

*=========*=========*=========*=========*=========*=========*
*=========*=========*=========*=========*=========*=========*



**************************
*     SUBROUTINE SUB1    *
**************************

      SUBROUTINE SUB1
      implicit double precision(a-h,j-z)

$include "orj.incl.f"

*******************************************************
* This subroutine reads in the a/c fixed data and sets  *
* constants, it is called from subroutine USERF.        *
*******************************************************

*  Reading-in all the fixed data for a particular aircraft
*  --------------------------------------------------------

      READ(11,1)DUMMY
      READ(11,*)DFUS,LF1,LF2,FINCID,IWING,VDIVE,IROWS

      READ(11,1)DUMMY
      READ(11,*)DNAC,LNAC,LN

      READ(11,1)DUMMY
      READ(11,*)ARH,TRH,TCH,VH,ITAIL,QHQ

      READ(11,1)DUMMY
      READ(11,*)ARV,TRV,TCV,VV,VSWEPD

      READ(11,1)DUMMY
      READ(11,*)ENGP,UCP
```

```
      READ(11,1)DUMMY
      READ(11,*)ENGL,ENGM,ENGLCC

      READ(11,1)DUMMY
      READ(11,*)TOT,SPEMPG,IENG,XXSFC,ENGSC

      READ(11,1)DUMMY
      READ(11,*)C1A,C1MAX,C1DES,CMACW,TCRTCW,wswepd

      READ(11,1)DUMMY
      READ(11,*)BFOB,CFOC,DFDLAN,IFLAP,MAXOV0,DC1MAX

      READ(11,1)DUMMY
      READ(11,*)RUFW,RUFF,RUFN

      READ(11,1)DUMMY
      READ(11,*)XXWIW,XXFUW,XXTAW,XXNAW,xxflaw

      READ(11,1)DUMMY
      READ(11,*)xxengw,xxucw,xxconw,xxsysw,xxfurw
      READ(11,1)DUMMY
      READ(11,*)NPAS

      READ(11,1)DUMMY
      READ(11,*)STAGE,INSTAG,DIVERS,HOLDMN,INHSEG,INCSEG

      READ(11,1)DUMMY
      READ(11,*)BFLMAX,LFLMAX,IMLAND,MINMRG,RODLIM

      READ(11,1)DUMMY
      READ(11,*)WATISA,WATH,GRAMIN, EMBST

      READ(11,1)DUMMY
      READ(11,*)JSUBC,JSRATE,JFWAST,JINHO,JIRATE,JUNCA

      READ(11,1)DUMMY
      READ(11,*)JURATE,JBOUT,JENGC,JOH,JWRATE,JWTIME

      READ(11,1)DUMMY
      READ(11,*)INUMAC,JFPRO,JDEVC,JCSC1,JCSC2,JCAM1

      READ(11,1)DUMMY
      READ(11,*)JCAM2,JCAM3,JCEM1,JCEM2,JCEM3,JCW

      READ(11,1)DUMMY
      READ(11,*)JPFUEL,JCLF1,IENTYP

1     FORMAT(A)

*   CURRENT VERSION LIMITED TO 2 ENGINES
      INENG=2

* Read-in the variables for PERI-OPT option
* ---------------------------------------
       READ (11,*)NVAR
       DO 100 I = 1, NVAR
        READ (11,1)LABVAR(I)
100    CONTINUE
```

```
* Read-in the constraints for PERI-CPT option
* ------------------------------------------
       READ (11,*)NCON
       DO 200 I = 1, NCON
        READ (11,1) LABCON(I)
200    CONTINUE

*  Scale Max. Take-Off Thrust
*  ------------------------
      TOT = TOT * ENGSC




      RETURN
      END


*=========*=========*=========*=========*=========*=========*
*=========*=========*=========*=========*=========*=========*



*************************
*   SUBROUTINE  USERF    *
*************************

      SUBROUTINE USERF (XX,CC,IOCODE,IOBJ,ICALLF,INFE)
      IMPLICIT DOUBLE PRECISION(A-H, J-Z)

$include "orj.incl.f"

**************************************************************
*      This is the main aircraft synthesis model             *
*      it calls all the estimating routines in turn          *
**************************************************************

*  Read in fixed aircraft data
*  ==========================
      IF(ICALLF.eq.0)CALL SUB1
      IF(ICALLF.eq.0)CLOSE(UNIT=11)


*  ASSIGN VARIABLES
*  ===============
      ARW     =  XX(1)
      SREF    =  XX(2)
      TRW     =  XX(3)
      TCW     =  XX(4)
      LF3     =  XX(5)*DFUS
      LFN     =  XX(6)*(LF1+LF2+LF3)
      DFDTO   =  XX(7)
      XMTO    =  XX(8)
      MFUEL   =  XX(9)
      TSET1   =  XX(10)
      VAIAS   =  XX(11)
      CRUTAS  =  xx(12)
      VCIAS   =  XX(13)
      HCRUZ   =  XX(14)
      SB1     =  XX(15)*STAGE
```

```
      SB2     =  XX(16)*STAGE
      SB3     =  XX(17)*DIVERS
      VBIAS3  =  XX(18)
      HCRUZ3  =  XX(19)
      TSET3   =  XX(20)

*  Keep crutas fixed value, vbias then falls out for any height
*  ============================================================
      vbias=crutas*sqrt(ro(hcruz,0.0d0)/ro(0.0D0,0.0D0))

*  Find cruise mach number
*  =======================
      airtem=288.16-.0065*hcruz
      cruzma=crutas/sqrt(402.16*airtem)

*  ASSIGN DIVERSION CLIMB/DESCENT IAS'S = MAIN MISSION IAS'S.
*  ==========================================================
      VAIAS3=VAIAS
      VCIAS3=VCIAS


*  Calculate all the aircraft geometry used in
*  the other estimating routines and segments.
*  -------------------------------------------
      CALL GEOM

*  Estimate the component masses and sum them
*  to obtain the aircraft mass parameters
*  ------------------------------------------
      CALL MASS

*  Calculate the aircraft centres of gravity
*  -----------------------------------------
      CALL CGCAL

*  Calculate the ZERO LIFT aerodynamic parameters
*  ----------------------------------------------
      CALL ZLAERO

*  Calculate the LIFT DEPENDANT aerodynamic parameters
*  ---------------------------------------------------
      CALL LDAERO


*  Calculate the second segment climb performance
*  ----------------------------------------------
      CALL SSGRAD


*  CALCULATE STATIC MARGIN AT ASSUMED WORST CASE
*  ---------------------------------------------
*  1) AT AFT CENTRE OF GRAVITY
      XAC=XACPOF
      CLAAPT=CLAAMT+CLAH*SH/SREF*(1.-DEDA)*QHQ
      XNP=XAC+MAC*CLAH/CLAAPT*(1.-DEDA)*VH*QHQ
      STATMR=(XNP-CGAFT)/MAC

*  2) AT DATUM FLIGHT CONDITION
      XNPNOR=XACPOF+MAC*CLAH/CLAAPT*(1.-DEDA)*VH*QHQ
      STANOR=(XNPNOR-CGNORM)/MAC
```

```
*  Perform the flight profile analysis
*  ------------------------------------
      CALL FLTPRO

*  Calculate the FIELD performance
*  --------------------------------
      CALL FIELD

*  Estimate aircraft price and operating costs
*  --------------------------------------------
      CALL COST

*  Calculate the maximum rate of descent of the aircraft
*  ------------------------------------------------------
      CALL ROD



*  ASSIGN CONSTRAINTS
*  ==================
      CC(1)  = -(STATMR-MINMRG)
      CC(2)  = -(MTOCAL-XMTO)
      CC(3)  = -(MFUCAL-MFUEL)
      CC(4)  = -(BFLMAX-BFL)
      CC(5)  = -(WATGRA-GRAMIN)
      CC(6)  = -(LFLMAX-LFL)
      CC(7)  = -(STAGE-(SA1+SB1+SC1))
      CC(8)  = -(STAGE-(SA2+SB2+SC2))
      CC(9)  = -(DIVERS-(SA3+SB3+SC3))
      CC(10) = -(0.80 -CRUZMA)
      CC(11) = -(CRUTAS - VCTAS)
      CC(12) = -(TIMC1 - MINTM)
      CC(13) = -(DRAGC-THC)
      CC(14) = -(DRAGD-THD)

*  ASSIGN OBJECTIVE FUNCTIONS
*  ==========================
      IF(IOBJ.EQ.1) F=MFUCAL
      IF(IOBJ.EQ.2) F=MTOCAL
      IF(IOBJ.EQ.3) F=DOCPF
      IF(IOBJ.EQ.4) F=SMC
      IF(IOBJ.EQ.5) F=MWING
      IF(IOBJ.EQ.6) F= MWING+MFUCAL

      CC(15)=F

*  ASSIGN VARIABLES FOR PERI-OPT OPTION
*  ====================================
      OPTVAL(1)  = MFUCAL
      OPTVAL(2)  = MTOCAL
      OPTVAL(3)  = DOCPF
      OPTVAL(4)  = SMC
      OPTVAL(5)  = MWING
      OPTVAL(6)  = MWING+MFUCAL
      OPTVAL(7)  = CRUZMA
      OPTVAL(8)  = BFL
      OPTVAL(9)  = LFL
      OPTVAL(10) = STATMR
      OPTVAL(11) = WATGRA
```

```
*  OPTIMISATION CONTROLS
*  ====================
      itern = nfe
      if (abs(itern - iterol) .eq. 100) goto 200
      IF(ICALLF.NE.3.AND.ICALLF.NE.4)RETURN

*  ASSIGN NAME TO FILE OF OPTIMUM A/C SPECIFICATION
*  ===============================================
      CALL COUA('<Filename for OPTIMUM free variables :> ')
      READ 1,FILOPT
1     FORMAT(A)

*  Fill Opt File with design variable values
*  ----------------------------------------
      OPEN(UNIT=9, FILE=FILOPT)
       DO 100  I = 1,50
        WRITE(9,2)XX(I)
2       FORMAT(F12.5)
100    CONTINUE

*  Fill Opt File with output values at optimum point
*  ------------------------------------------------

      write(9,3)
3     format('**************')
      write (9,4)npas,
     $       stage*0.00054, bflmax*3.2808, lflmax*3.2808,
     $       arw, sref*3.2808*3.2808, lf*3.2808,
     $       mempty*2.205, moem*2.205, mtocal*2.205,
     $       dfdto, clmtrt, dfdlan,clmtrl,
     $       cruzma, vbias*1.9426,hcruz*3.2808,
     $       mfbmai*2.205, mfucal*2.205, tstage,
     $       vstalt*1.9426, vstall*1.9426,
     $       watgra, bfl*3.2808, lfl*3.2808,
     $       pac/1e6, docpf, docpm, smc
4     format(29(f10.2,/))
      CLOSE(UNIT=9)

200   continue

*  Open Tempory File and Fill with output values
*  --------------------------------------------
      IF(ICALLF.NE.3.AND.ICALLF.NE.4) then
      iunit = 13
      open(unit=iunit,file='Temp.res')
      else
       iunit = 12
      endif


*  Record failiure position and fill tempory file with
*  current values. This is used for fault diagnosis.
*  ---------------------------------------------------
        if (iunit .eq. 13) then
          write(iunit,876) nfe
876      format('Stopped after ',i5,' Calls to userf')
        endif

      iu=iunit
```

```
* =============
* PRINT RESULTS
* =============

*  Assign text to dummy variables
*  ------------------------------
      IPASNO = NPAS
      IIENGP = ENGP
      IF(IWING .EQ. 1)  TEMPC1 ='High Wing Configuration'
      IF(IWING .EQ. 0)  TEMPC1 ='Low  Wing Configuration'
      IF(ITAIL .EQ. 1)  TEMPC2 ='T - Tail Configuration'
      IF(ITAIL .EQ. 0)  TEMPC2 ='Fuselage Mounted Tailplane'
      IF(IIENGP .EQ. 1) TEMPC3 ='Wing Mounted Engines'
      IF(IIENGP .EQ. 0) TEMPC3 ='Rear Fuselage Mounted Eng.'
      IF(IFLAP .EQ. 1)  TEMPC4 ='SINGLE-SLOTTED FLAPS'
      IF(IFLAP .EQ. 2)  TEMPC4 ='DOUBLE-SLOTTED FLAPS'
      IF(IFLAP .EQ. 3)  TEMPC4 ='SINGLE-SLOTTED FOWLER FLAPS'
      IF(IFLAP .EQ. 4)  TEMPC4 ='DOUBLE-SLOTTED FOWLER FLAPS'
      IF(IENTYP .EQ. 1) TEMPC5 ='CFE-738 Engine'
      IF(IENTYP .EQ. 2) TEMPC5 ='RR-Allison Engine'
```

At this point the program contains the format instructions for the output as shown in appendix F.

The program continues with each of the subroutines called in USERF (E5/6).

The program ends with the subroutines associated with the PERI-OPT option

The design synthesis and PERI-OPT code is written in Standard Fortran 77 (approximately 4000 lines in length).

A full listing may be obtained from L.R.Jenkinson, Department of Transport Technology, Loughborough University of Technology, Leicestershire, LE11 3TU

APPENDIX F

This appendix contains the text from a specimen input file and the corresponding output file. The optimisation study chosen as the sample is taken from the 'generalised studies' as this shows the finally developed format of both files. The study point selected is the central point in the study, namely:-

Number of passengers	=	72
Stage distance (nm)	=	1250
Field length (ft)	=	6100

The point design converged after 3826 trial designs and no constraints are violated.

The following pages contain the original file text and some explanatory notes. These notes are printed in *italic* font to distinguish them from the file data.

SPECIMEN INPUT FILE

The VARIABLES data defines all the design variables. The first two digits numerate the variable. The next digit is a control parameterr (0 = variable fixed at the starting value, 1 = variable left free). SCALE is the normalising number. INITIAL is the value of the variable at the start of the search. MIN./MAX. are the lower and upper values of the variable.

Input file : fjx-34-b

```
VARIABLES
*
*    Scale           Initial      Minimum      Maximum      Name
*
01 0 20.0            9.30         7.5          13.5         ARW          Wing Aspect Ratio
02 1 60.0            63.78        35.0         100.0        SREF         Wing Gross Area (sq m)
03 1 1.0             0.24         0.24         1.0          TRW          Wing Taper Ratio
04 1 0.16            0.14         0.1          0.15         TCW          Wing Thickness Ratio
05 0 3.0             3.0          2.0          4.0          LF3/DFUS     Fuselage Length Ratio
06 1 0.5             0.33         0.10         0.7          LFN/LF       Wing/Fuse Position Ratio
07 1 15.0            23.33        0.0          40.0         DFDTO        Take-Off Flap Deflection (deg)
08 1 20000.          29000.       9000.        50000.       XMTO         Aircraft MTO Mass (kg)
09 1 400.            4400.        100.         10000.       XMFUEL       Aircraft Fuel Mass (kg)
10 1 1.0             0.86         0.5          1.0          TSET         Engine Thrust Setting in Cruise (%)
11 1 90.             113.57       50.          149.         VAIAS        Climb Airspeed (IAS, m/s)
12 1 100.            234.89       80.          350.         crutas       Cruise Airspeed (TAS, m/s)
13 1 100.            141.21       50.          149.         VCIAS        Descent Airspeed (IAS, m/s)
14 1 9000.           9900.        5525.        10970.       HCRUZ        Cruise Altitude (m)
15 1 0.5             0.81         0.2          1.0          SB1/STAGE    Cruise Segment (First Stage)
16 1 0.5             1.00         0.2          1.0          SB2/STAGE    Cruise Segment (Notional Stage)

17 1 0.5             0.27         0.2          1.0          SB3/DIVERS   Cruise Segment (Diversion)
18 1 90.             89.53        30.          164.         VBIAS3       Diversion Cruise Airspeed (IAS, m/s)
19 1 6000.           6096.        1000.        6096.        HCRUZ3       Diversion Altitude (m)
20 1 1.0             0.41         0.25         1.0          TSET3        Diversion Engine Setting
21 1 1.0             1.40         0.50         3.00         ENGSC        Engine Scale Factor
*
```

The FUNCTIONS data defines the constraints and the objective function. The first two digits numerate the constraints. The next digit defines the type (1 = equality, -1 = inequality, 0 = objective function). The fourth digit allows the constraint to be ignored.

```
FUNCTIONS
01 1  0  1.0                 STATMR=MINMRG            Min. Static Margin
02 1  0  25000.              MTOCAL=XMTO              Mas Iteration Control
03 1  0  3000.               MFUCAL=XMFUEL            Fuel Iteration Control
04 -1 0  2500.               BFL   <BFLMAX            Max. Balanced Field Length
05 -1 0  0.05                WATGRA>GRAMIN            Min. Single-engine Climb Gradient
06 -1 0  2500.               LFL   <LFLMAX            Max. Landing Field Length

07 1  0  2000000.            STAGE =SA1+SB1+SC1       Stage Distance Control
08 1  0  2000000.            STAGE =SA2+SB2+SC2              "
09 1  0  2000000.            DIVERS=SA3+SB3+SC3              "

10 -1 0  1.0                 CRUZMA < 0.80            Max. Cruise Mach Number
11 -1 0  220.0               VCTAS < CRUTAS           Max. Descent Airspeed
12 -1 0  5000.               Rate of Descent          Rate of Descent Control
13 1  0  25000.              Main Cruise T=D          Aerodynamic Balance
14 1  0  25000.              Div. Cruise T=D                 "
15 0  0  1500.            3  OBJECTIVE FUNCTION (1=MFUCAL,2=MTOCAL,3=DOCPF)
*
```

The CONTROLS data defines the RQPMIN optimiser parameters. In the example below most of these parameters are unspecified and assume their default values as shown in the output.

```
CONTROLS
RFREQ=100            Frequency of reporting stage results
NFEMAX=20000         Max. number of calls to synthesis module
XTOLU = 1.0E-4       Tolerance on objective function slope
XTOLV = 1.0E-4       Tolerance on constraint vector slope
RUN
```

This data block defines the fixed input values.

```
DFUS------LF1-------LF2-------FINCID----IWING-----VDIVE-----IROWS-----   Fuselage (etc) geometry
2.89       4.0       19.65      3.0       0          205.       4
DNAC------LNAC------LN--------                                           Nacelle geometry
1.00       3.3       2.0
ARH-------TRH-------TCH-------VH--------ITAIL-----QHQ-------             Horizontal tail parameters
4.7        0.5       0.11      1.134      0         0.95
ARV-------TRV-------TCV-------VV--------VSWEPD----                       Vertical tail parameters
3.0        0.5       0.11      0.08       31.39
ENGP----UCP-----                                                         Aircraft layout
1          1
ENGL------ENGM------ENGLOC------                                         Engine geometry
2.0        585.      3.81
TOT-----SPEMPG----IENG------XXSFC                                        Engine performance
6515.      0.38      1         1.0
C1A-------C1MAX-----C1DES-----CMACW-----TCRTCW----wswepd                 Wing aerodynamic parameters
6.1        1.7       0.3       -0.08      1.1       21.5
BFOB------CFOC------DFDLAN----IFLAP-----MAXOV0----DC1MAX----             Flap parameters
0.75       0.30      40.0      3          1.0       0.0
RUFW------RUFF------RUFN------                                           Aerodynamic drag factors
1.2        1.2       1.8
XXWIW-----XXFUW-----XXTAW-----XXNAW-----xxflaw                           Mass factors
1.         1.        1.        1.         1.
xxengw----xxucw-----xxconw----xxsysw----xxfurw                           Mass factors
1.         1.        1.        1.         1.
NPAS------                                                               Number of passengers
72.
STAGE-----INSTAG----DIVERS----HOLDMN----INHSEG----INCSEG----             Mission specification
2314815.   1         185000.   45.        7         5
BFLMAX----LFLMAX----IMLAND----MINMRG----RODLIM----                       Field specification
1859.      1859.     2         0.05       11.953
WATISA----WATH------GRAMIN----EMBST                                      Single-engine climb specification
+20.       0.0       0.024     1.0
```

```
JSUBC-----JSRATE----JFWAST----JINHO-----JIRATE----JUNCA-----          Cost coefficients
0.22      20.0      1.04      0.545     8.5       0.062
JURATE----JBOUT-----ENGC---------JOH-------JWRATE----JWTIME----           "
6.0       50000.    950000.      3.87      3.0       1.034
INUMAC----JFPRO-----JDEVC-----JCSC1-----JCSC2-----JCAM1-----              "
200       1.1       1.E8      0.0708     0.015      10.0
JCAM2-----JCAM3-----JCEM1-----JCEM2-----JCEM3-----JCW-------              "
0.2E-3    0.5E-5    2.0       0.4E-3    0.3E-4    102400.
JPFUEL----JCLF1-----ENGTYP----                                            "      (and engine type)
0.0256    0.0          2
```

This data block defines the PERI-OPT parameter lists.

```
19
Wing Aspect Ratio                            Wing Area (sq. m)
Taper Ratio of Wing                          Thickness Chord Ratio Wing
LF3/Fuselage Diameter                        LFN/Fuselage Length
Flap Deflection at Take-Off (deg)
Empty Takeoff Weight (kg)                    Fuel Mass (Kg)
Thrust Setting (%)
Indicated Climb Airspeed (m/s)               True Cruise Airspeed (m/s)
Indicated Cruise Airspeed (m/s)              Cruise Height (m)
SB1/STAGE           SB2/STAGE                SB3/DIVERS
Indicated Diversion Airspeed (m/s)           Diversion Cruise Height (m)

11
Fuel Mass (kg)                               Empty Weight (kg)
Direct Operating Costs ($)                   Seat Mile Cost (cents)
Wing Mass (kg)                               Wing Mass + Fuel Mass (kg)
Cruise Mach No.
Balanced Field Length (m)                    Landing Field Length (m)
Static Margin                                WAT Gradient
```

SPECIMEN OUTPUT FILE

```
1Program  RQPMIN  Version Ver 1.0b For Mac II         00:00:00

 ANALYSIS OF  INPUT FILE DATA  AND  CONTROL PARAMETERS

 Input file: fjx-34-b
 Output file: fjx-34-b.res
```

Variable data   ***(Records input variable values in normalised format)***

Number of variables =   21

Index	Status	Scale	Starting value	Lower bound	Upper bound
1	0	0.2000000E+02	0.4650000E+00	0.3750000E+00	0.6750000E+00
2	1	0.6000000E+02	0.1063000E+01	0.5833333E+00	0.1666667E+01
3	1	0.1000000E+01	0.2400000E+00	0.2400000E+00	0.1000000E+01
4	1	0.1600000E+00	0.8750000E+00	0.6250000E+00	0.9375000E+00
5	0	0.3000000E+01	0.1000000E+01	0.6666667E+00	0.1333333E+01
6	1	0.5000000E+00	0.6600000E+00	0.2000000E+00	0.1400000E+01
7	1	0.1500000E+02	0.1555333E+01	0.0000000E+00	0.2666667E+01
8	1	0.2000000E+05	0.1450000E+01	0.4500000E+00	0.2500000E+01
9	1	0.4000000E+03	0.1100000E+02	0.2500000E+00	0.2500000E+02
10	1	0.1000000E+01	0.8600000E+00	0.5000000E+00	0.1000000E+01
11	1	0.9000000E+02	0.1261889E+01	0.5555556E+00	0.1655556E+01
12	1	0.1000000E+03	0.2348900E+01	0.8000000E+00	0.3500000E+01
13	1	0.1000000E+03	0.1412100E+01	0.5000000E+00	0.1490000E+01
14	1	0.9000000E+04	0.1100000E+01	0.6138889E+00	0.1218889E+01
15	1	0.5000000E+00	0.1620000E+01	0.4000000E+00	0.2000000E+01
16	1	0.5000000E+00	0.2000000E+01	0.4000000E+00	0.2000000E+01
17	1	0.5000000E+00	0.5400000E+00	0.4000000E+00	0.2000000E+01
18	1	0.9000000E+02	0.9947778E+00	0.3333333E+00	0.1822222E+01
19	1	0.6000000E+04	0.1016000E+01	0.1666667E+00	0.1016000E+01
20	1	0.1000000E+01	0.4100000E+00	0.2500000E+00	0.1000000E+01
21	1	0.1000000E+01	0.1400000E+01	0.5000000E+00	0.3000000E+01

```
Problem function data      (Records the constraint values in normalised format)
---------------------

Number of constraints =    14

Index    Status     Type          Scale                Index    Status     Type          Scale
    1         1        0      0.1000000E+01                2         1        0      0.2500000E+05
    3         1        0      0.3000000E+04                4        -1        0      0.2500000E+04
    5        -1        0      0.5000000E-01                6        -1        0      0.2500000E+04
    7         1        0      0.2000000E+07                8         1        0      0.2000000E+07
    9         1        0      0.2000000E+07               10        -1        0      0.1000000E+01
   11        -1        0      0.2200000E+03               12        -1        0      0.5000000E+04
   13         1        0      0.2500000E+05               14         1        0      0.2500000E+05
   15         0        0      0.1500000E+04

objective is function    15                  problem number =     3


Control parameters     (Records the RQPMIN parameter values including the default values)
------------------

nfemax = 20000     nimax  =  1000     nsmax  =    20
nsetc  =     4     nsetcf =     8     nsetv  =     4     nsetvf =     8
ofreq  =     0     ofrom  =     0     rfreq  =   100     rfrom  =     1

centrl = F     fdset  = F     norep  = F     cheats = T     fast   = T     quasi  = T
fixrp  = F     timid  = F     monitr = F     nofrec = F     yesbc  = F     shrnk  = T     projct = T

xtol   =  0.1000000E-05    xtolu  =  0.1000000E-03    xtolv  =  0.1000000E-03    gtol   =  0.1000000E-02
rtol   =  0.1000000E+00    omegar =  0.1000000E+00    rpmax  =  0.2000000E+00
umin   =  0.1000000E-05    vminf  =  0.1000000E-02    vminc  =  0.1000000E-05    ctol   =  0.1000000E-02
umax   =  0.1000000E+00    vmax   =  0.1000000E+00    omega  =  0.1000000E+00    mu     =  0.1000000E-03
bdtol  =  0.1000000E+00    lmtol  =  0.1000000E+00    mtol   =  0.5000000E+00    cmax   =  0.1000000E-01
subtol =  0.1000000E-02    qrtol  =  0.1000000E+02    bfstol =  0.1000000E-05    diftol =  0.5000000E-03
ztol   =  0.1000000E-29


End of input data

-----------------
```

```
1Program  RQPMIN  Version Ver 1.0b For Mac II          00:00:00

STARTING POINT
```

free variables *(Records the initial values of all the variables in normalised format)*

```
 2  0.106300E+01  3  0.2400000+00  4  0.875000E+00  6  0.660000E+00  7  0.1555333E+01  8  0.1450000E+01  9  0.1100000E+02
10  0.860000E+00 11  0.126188E+01 12  0.234890E+01 13  0.141210E+01 14  0.1100000E+01 15  0.1620000E+01 16  0.2000000E+01
17  0.540000E+00 18  0.994777E+00 19  0.101600E+01 20  0.410000E+00 21  0.140000E+01
```

objective function *(Shows the initial calculation of the objective function)*

```
f(x) =  0.2623449E+01
```

equality constraints *(Records the initial values of the constraints)*

```
 2 -0.696818E-02  3  0.498988E-01  7 -0.757211E-01  8 -0.757211E-01  9 -0.671270E-03 13 -0.820641E-02 14 -0.5462112E-04
 1 -0.252101E-01
```

active inequality constraints *(Records the initial values of the constraints)*

```
11  0.3173764E-01  5  0.8068629E-01
```

inactive inequality constraints *(Records the initial values of the constraints)*

```
12 -0.3907811E-01  4  0.1396274E-02 10 -0.1706565E-01  6 -0.4178356E-01
```

The next eight pages show the optimum aircraft configuration.

The data is presented in both SI and Imperial units.

```
========================================
  Number of Passengers    ****    72 ****

  **** Pseudo RR-Allison Engine *****

  Take-Off Thrust (lbs)   ****   9758. ****

  Engine Scale Factor     ****   1.498 ****

========================================
```

```
===============================
DESIGN LOAD LIMITS  (ultimate)
===============================

   Load Gust Factor                        =      4.73
   Manouvre Load Factor                    =      4.00
   Design Dive Speed  (I.A.S)  m/s (ft/s)  =    205.00   (    672.40 )
```

GEOMETRIC DATA

	Units	WING		TAILPLANE		FIN	
Aspect Ratio		9.30		4.70		3.00	
Gross Area	sq.m (sq.ft)	59.39	(638.99)	10.49	(112.88)	6.15	(66.18)
Span	m (ft)	23.50	(77.08)	7.02	(23.03)	4.30	(14.09)
Taper Ratio		0.24		0.50		0.50	
Thickness Chord ratio		0.13		0.11		0.11	
Mean Aer. Chord	m (ft)	2.84	(9.33)	1.49	(4.90)	1.43	(4.70)
Chord at C.Line	m (ft)	4.08	(13.37)	1.99	(6.53)	1.91	(6.26)
Tail Arm	m (ft)			18.25	(59.87)	18.15	(59.54)
Fin Sweep	degrees	21.50					

Wing Location m (ft) 10.71 (35.14)
From Nosecone Apex to the Leading edge at Centreline

**** Low Wing Configuration ****
**** Fuselage Mounted Tailplane ****
**** Wing Mounted Engines ****

			Fuselage		One-Nacelle	
Diameter	m	(ft)	2.89	(9.48)	1.00	(3.28)
Total Length	m	(ft)	32.32	(106.01)	3.30	(10.82)
Nose Cone Length	m	(ft)	4.00	(13.12)	2.00	(6.56)
Cabin Length	m	(ft)	19.65	(64.45)		
Tail cone Length	m	(ft)	8.67	(28.44)	1.30	(4.26)
Wetted Area	m	(ft)	264.68	(2849.04)	7.69	(82.82)

MASS STATEMENT

Wing Incl. Flaps	kg	(lbs) =	2855.19	(6281.42)
Flaps	kg	(lbs) =	651.21	(1432.66)
Fuselage	kg	(lbs) =	4718.72	(10381.19)
Nacelles (TOTAL)	kg	(lbs) =	1073.34	(2361.35)
Empennage	kg	(lbs) =	253.22	(557.08)
Propulsion Group	kg	(lbs) =	2067.75	(4549.06)
Undercarriage	kg	(lbs) =	1174.26	(2583.36)
Surface Controls	kg	(lbs) =	467.91	(1029.39)
Systems	kg	(lbs) =	2341.73	(5151.81)
Furnishings	kg	(lbs) =	2100.00	(4620.00)
EMPTY MASS	kg	(lbs) =	17052.11	(37514.65)
Operation items	kg	(lbs) =	144.00	(316.80)
Crew Mass	kg	(lbs) =	270.00	(594.00)
OP. Empty Mass	kg	(lbs) =	18339.42	(40346.73)
Payload	kg	(lbs) =	6531.84	(14370.05)
Zero Fuel Mass	kg	(lbs) =	24871.26	(54716.77)
Total Fuel	kg	(lbs) =	4485.14	(9867.31)
MAXIMUM TAKEOFF	kg	(lbs) =	29356.40	(64584.08)

C.G. POSITIONS FROM NOSE APEX

Empty Aircraft	m	(ft) =	14.41	(47.28)
Datum Position				
----50% Fuel Full Payload	m	(ft) =	14.16	(46.45)
AFT Limit	m	(ft) =	14.80	(48.53)
Forward Limit	m	(ft) =	13.80	(45.26)

AERODYNAMIC DATA

ZERO-LIFT DRAG COEFFICIENTS BASED ON GROSS WING AREA

Exposed Wing	=	0.0068
Fuselage	=	0.0109
Nacelles (Total)	=	0.0033
Horizontal Tail	=	0.0016
Vertical Tail	=	0.0009
Interference	=	0.0006

LIFT-DRAG POLAR (Trimmed A/C, Datum C.G., Power-Off.)

CL	CD
0.00	0.0250
0.20	0.0257
0.40	0.0299
0.60	0.0377
0.80	0.0489
1.00	0.0637
1.20	0.0820
1.40	0.1038
1.60	0.1291

Neutral Point (POWER-OFF) m (ft) = 14.9383 (48.9976) From Nose.
Static Margin (DATUM C.G., POWER-OFF) = 0.2727

SINGLE-SLOTTED FOWLER FLAPS

	Flap Defln. ---deg-----	Section CL ---max----	Wing CL --max--	Trimmed a/c CL ------max-----
TAKEOFF	24.5335	3.2419	2.4403	2.3838
LANDING	40.0000	3.4952	2.6073	2.5389

MISSION ANALYSIS

CRUISE MACH NO. >>>>>>>>>> 0.79 <<<<<<<<<<

FIRST STAGE

Initial mass kg (lbs) = 29356.   (64584.)

		CLIMB	CRUISE	DESCENT
Distance	m	135881.9	2034561.6	144371.5
	ft	445692.6	6673362.2	473538.4
Fuel Burn	kg	487.7	2843.2	129.6
	lbs	1072.8	6255.1	285.2
Time	s	825.7	8556.4	802.3
IAS	m/s	120.6	140.1	140.0
	ft/s	395.8	459.5	459.3
	Knots	234.3	272.1	272.0
	mph	269.8	313.3	313.2

Cruise Altitude m (ft) = 9756. (32001.)
Cruise Thrust Setting (%) = 82.

R.O.D/C

Start of CLIMB	units m/s (ft/s)	=	16.438	(53.916)
End of CLIMB	units m/s (ft/s)	=	7.512	(24.638)
Start of DESCENT	units m/s (ft/s)	=	-14.038	(-46.043)
End of DESCENT	units m/s (ft/s)	=	-10.567	(-34.661)

DIVERSION STAGE

Initial mass kg (lbs) = 25851. (56871.)

		CLIMB	CRUISE	DESCENT
Distance	m	48613.7	50890.1	85496.2
	ft	159452.9	166919.5	280427.6
Fuel Burn	kg	234.7	84.9	98.9
	lbs	516.4	186.8	217.7
Time	s	340.6	408.9	524.4
IAS	m/s	120.6	90.8	140.0
	ft/s	395.8	298.0	459.3
	Knots	234.3	176.4	272.0
	mph	269.8	203.2	313.2

Cruise Altitude m (ft) = 6091. (19977.)
Cruise Thrust Setting (%) = 39.

R.O.D/C

Start of DESCENT	units m/s (ft/s)	=	-12.735	(-41.771)
End of DESCENT	units m/s (ft/s)	=	-10.596	(-34.755)

SUMMARY OF FUEL TOTAL FUEL BURN

Total mission fuel	kg (lbs)	=	3506.	(7713.)
Inc. Ground Man. fuel	kg (lbs)	=	45.	(100.)
Diversion fuel burn	kg (lbs)	=	419.	(921.)
Holding fuel burn	kg (lbs)	=	561.	(1233.)
GRAND TOTAL FUEL BURN	kg (lbs)	=	4485.	(9867.)
AVERAGE STAGE TIME	secs	=	10184.	

```
===============================
FIELD PERFORMANCE (SL-ISA)
===============================

  Second Segment Gradient                =      0.0317
  Balanced Field Length  m    (ft   ) =    1859.0  (     6097.5 )
  Takeoff Stall Speed    m/s  (knots)=      57.7  (      112.0 )
  Landing Mass           kg   (lbs ) =   25850.5  (    56871.1 )
  Landing Field Length   m    (ft   ) =    1859.0  (     6097.5 )
  Landing Stall Speed    m/s  (knots)=      52.4  (      101.8 )


===============================
WAT PERFORMANCE
===============================

  AT ISA +  20. Degrees Centigrade
  Elevation              m    (ft   ) =       0.0  (        0.0)
  Second segment climb gradient      =      0.0240
```

```
====================================
COST ESTIMATION (U.S.DOLLARS 1988 )
====================================

 2500hr/yr & Stage Length m ( nm ) =   2314815.0  (      1250.0)


           Fuel price ($/USG)         =          0.75
           Fuel Used  (lbs. )         =       7730.5
           Block Time (Hours)         =          2.947

           Price of Airframe          =   11975641.7
           Price of Engines           =    2750560.8
           Price of Aircraft          =   14726202.5

           COSTS per FLIGHT (STAGE)
           ------------------------
           Standing Charge            =       1674.0
           Aircraft Maintnce          =       1077.5
           Fuel & Oil                 =        886.3
           Crew cost                  =        554.1
           Landing Fees               =          0.0
           TOTAL DOC per FLIGHT ($)   =       4191.9
           TOTAL DOC per MILE   ($)   =          3.35
           SEAT MILE COST (c/nm.)     =          4.66


 @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

 1Program  RQPMIN  Version Ver 1.0b For Mac II          00:00:00

  end of iteration number    80
  ----------------------------

  CONVERGENCE DETECTED  [ Code A ]     after  3826 calls to user routine
```

The last two pages list the optimiser values at the end of the search, in normalised format.

```
free variables
--------------
 6  0.662896E+00 12  0.237692E+01 20  0.390837E+00 15  0.175786E+01 14  0.108404E+01  8  0.146782E+01 21  0.1497721E+01
13  0.140004E+01  2  0.989757E+00  7  0.163556E+01 10  0.818056E+00  9  0.112128E+02 17  0.550163E+00 16  0.2000000E+01
 4  0.839698E+00 18  0.100921E+01 11  0.134038E+01

variables fixed at or near their lower bounds
---------------------------------------------
 3  0.2400000E+00

variables fixed at or near their upper bounds
---------------------------------------------
19  0.1015084E+01

objective function
------------------
f(x) =  0.2794592E+01

equality constraints
--------------------
 2 -0.1906535E-12  3  0.6964784E-09  7  0.117294E-09  8  0.117294E-09  9  0.602592E-11 13 -0.257670E-08 14 -0.605154E-10
 1  0.3847229E-08

active inequality constraints
-----------------------------
11 -0.2341002E-10  5  0.2528111E-11  4  0.3734232E-12  6  0.5342689E-10

inactive inequality constraints
-------------------------------
10 -0.9370045E-02 12 -0.4971480E-01
```

RQPMIN Operational data, in normalised format.

```
Lagrange multiplier estimates
-----------------------------

 2 -0.5832436E+00  3 -0.2895999E+00  7 -0.117284E+01  8 -0.117284E+01  9 -0.315667E+00 13 -0.728772E+00 14 -0.866289E-01
 1  0.1687547E+00 11  0.2290552E+00  5  0.125540E+00  4  0.723335E+00  6  0.193632E+00
```

`Partial derivatives of Lagrangian function` ***(design surface slope data)***

```
-----------------------------------------

 6  0.1219727E-18 12 -0.8131516E-19 20 -0.677626E-19 15  0.379470E-18 14  0.125784E-18  8 -0.27952E-19 21  0.200746E-18
13 -0.2181110E-19  2  0.6776264E-19  7  0.338813E-20 10  0.313402E-19  9 -0.960823E-04 17 -0.48457E-05 16  0.000000E+00
 4 -0.1024278E-05 18 -0.1265765E-04 11  0.140309E-04  3  0.868986E-01 19 -0.433212E-02
```

`Norms of active constraint gradients` ***(Constraint boundary data)***

```
-----------------------------------
 2  0.7128040E+00  3  0.1525107E+01  7  0.626383E+00  8  0.626383E+00  9  0.665347E-01 13  0.20744E+01 14  0.163806E+01
 1  0.3190042E+01 11  0.1077169E+01  5  0.168821E+01  4  0.666389E+00  6  0.583801E+00
```

```
convergence criteria
--------------------

pdatum =  0.2794592E+01    ldatum =  0.2794592E+01    gdatum =  0.2196027E-16
nu     =  0.0000000E+00    numax  =  0.2944092E+02
unormx =  0.2234386E-08    unormd =  0.2234386E-08    rtol   =  0.1000000E-01    xtolu  =  0.1000000E-03
vnormx =  0.9608236E-04    vnorm  =  0.9608236E-04    xtolv  =  0.1000000E-03    grdldn =  0.9608236E-04
nde    =  0                ndef   =  70               ndec   =  61               ncalls =  309          nfuncs =   178
```