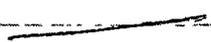
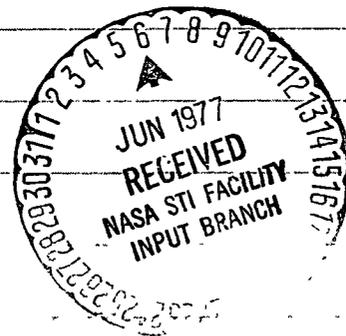


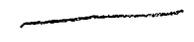
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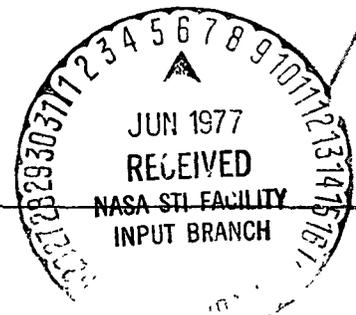
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16. Abstract <p>A survey of new equipment and operational concepts affecting aircraft in the terminal area is reported. The concepts considered to have a major impact on future air carrier operations are identified. Of those, curved approach applications and modified climb and descent procedures for minimum fuel consumption are considered in detail. The curved approach study involves, as a principal example, the application of MLS guidance to enable execution of the current visual approach to Washington National Airport under instrument flight conditions. The study considers the operational significance and the flight path control requirements involved in the application of curved approach paths to this situation. The energy management study involves consideration of alternative flight path control regimes to achieve minimum fuel consumption subject to constraints related to air traffic control requirements, flight crew and passenger reactions, and airframe and powerplant limitations. Extensive simulation is conducted to evaluate the time and fuel benefits associated with modified climb and descent procedures. Both studies conclude with the specification of flight test experiments to evaluate the concepts considered in a realistic environment.</p>					
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## EXECUTIVE SUMMARY

### OBJECTIVES

The development and application of new equipment and revised procedures affecting future aircraft operations in the terminal area will undoubtedly evolve from the constraints hindering current operations. The considerations due to energy conservation, noise abatement, and safe, efficient air traffic control are all principal causal factors. The intent of this study was to examine these factors further and suggest a practical approach to cope with these limitations on terminal area operations. To accomplish this goal, the following general objectives were established.

- Suggest a realistic projection of the future terminal area operational environment.
- Develop the basis for a terminal area systems performance evaluation.
- Propose flight experiments involving advanced concepts.

Based on these objectives, the following methodology was applied to evaluate new equipment applications and control procedures relevant to terminal area operations.

### APPROACH

To identify the prime factors affecting the evolution of terminal area systems, a review of the current programs and future plans of the FAA and NASA was conducted. Also, interviews were arranged with informed personnel of the Department of Transportation (the Transportation Systems Center and the Systems Research and Development Service of the FAA). These activities prompted the decision to concentrate on two general aspects of terminal area operations. These two study categories involved:

- The application and implementation of curved approach paths to reduce the impact of noise.
- The design and evaluation of modified vertical flight path control regimes to minimize energy consumption.

Both of these concepts were examined with respect to the operational constraints imposed by current standards and also those anticipated for the future terminal area environment. Simulation models were developed for both the aircraft and its control systems to evaluate the functional design concepts identified as appropriate solution methods. For the curved profile study, the approach to Washington National Airport was selected as the basis for evaluation. For the energy management study, the Boeing 737-200 and the McDonnell-Douglas DC-10-10 were chosen as representative aircraft systems. In both studies, the research effort concluded with the definition of flight test experiments to validate the suggested concepts in a realistic operational environment.

#### SUMMARY OF RESULTS

An arc-segment approach utilizing MLS guidance and duplicating the current visual River approach to Washington National was proposed as the means to minimize noise exposure under instrument flight conditions. The operational benefits expected from the implementation of this procedure are discussed. A control system design based on current autopilot technology was suggested and evaluated with respect to the Washington National curved approach. The control system demonstrated reasonable performance when exercised for various error sources and perturbations. Also, an estimation algorithm to derive the orientation of the aircraft velocity vector from MLS measurement data was proposed and evaluated. The concluding effort involved the definition of a series of flight tests to be conducted at the FAA's National Aviation Facilities Experimental Center

to evaluate the viability of the curved approach concept.

A simulation model to approximate the functional characteristics of an aircraft and its powerplant was developed and verified by comparing the results derived from the simulation of standard climb and descent procedures with data from aircraft operational handbooks. Six alternative flight path control regimes were suggested as possible procedures to realize reduced energy consumption. These methods were applied to both the B737 and DC-10 simulation models and all of these demonstrated measurable fuel savings. However, with respect to the total cost of operation, variations in the time of flight due to the modified climb and descent procedures diminish the overall operational benefits. In this context, the B737 demonstrated insignificant savings for the modified control regimes while the costs per climb/descent operation of the DC-10 were reduced by \$1.70 to \$5.20. The investigation of energy management concepts also concluded with the specification of a series of flight tests involving the NASA TCV research aircraft to evaluate the actual benefits expected with the modified flight path control procedures.

## 1.1 STUDY OBJECTIVES

Over the next ten to fifteen years the emphasis in civil aviation will likely be directed toward a more serious and comprehensive consideration of the constraints due to energy conservation, noise abatement and efficient air traffic control, as well as the ever present consideration of the minimization of direct operating costs. The development and application of new equipment technology and capabilities as well as revised operating procedures in response to these newly emphasized constraints could well have a profound effect upon the manner in which civil aircraft are both equipped and operated. For instance, the onboard computer capabilities anticipated in future aircraft designs will enable the definition of minimum energy climb and descent procedures resulting in considerably different vertical profiles (both altitude-time and altitude-distance) than current minimum time procedures. The use of minimum energy profiles will in turn affect air traffic control procedures, aircraft control procedures and the pilot's display requirements. Also, the introduction of MLS will enable the execution of curved approach and departure paths under IFR conditions to avoid noise sensitive areas in the terminal environment. In addition, other operating constraints will also affect airborne and ATC procedures. The interaction of these constraints and their impact on both hardware modifications and procedure revisions must be systematically evaluated. The TCV program offers an excellent opportunity to provide basic research data on the effect of these new potential constraints upon the aircraft performance and the aircraft control procedures.

Over the next few years several new technology avionics items will be developed by FAA, NASA and industry. This new avionics equipment, plus existing avionics, can be used in conjunction with computer software to produce lateral

and vertical aircraft guidance signals for the flight control system and the pilot. Through software processing of the avionics signals, the solution to sophisticated guidance equations can be developed and evaluated. In this manner guidance signals for minimum energy profiles, minimum noise profiles, minimum time profiles or some other type of vertical profile, can be used by the aircraft flight control system. In a similar manner, various lateral guidance equations can be processed to permit advanced concepts such as curved arrival and departure routes to be flown. The use of the TCV aircraft will permit flight test data to be collected for these and other advanced lateral and vertical profile concepts. However, in a complex set of interacting elements as represented by the high density terminal area air traffic control environment and the diverse set of aircraft and electronics which could potentially operate in such an environment, these advanced concepts should be studied as part of a fresh, innovative look at the entire problem. Constraints should be imposed more from the viewpoint of available or anticipated hardware and software technology overlaid on a pragmatic evaluation of the realities of the air traffic control system rather than solely by recourse to historical procedures and techniques. It is with this viewpoint that this study has been configured. It combines an analysis of the future terminal area route design (approached from the standpoint of meeting the demands of emerging priorities such as energy and noise), and a technical evaluation of the application of advanced airborne software and hardware techniques. This study addresses the solutions to these problems and considers an analysis of the sensitivity of these solutions to the available or potential performance characteristics of the several elements of the airborne systems. This effort logically concludes with the definition of a set of operational experiments utilizing the TCV research tool to evaluate the feasibility and validity of the procedures and systems developed during the preceding study.

## 1.2 APPROACH

Currently, several projects at the FAA and NASA affecting future terminal area operations are being considered. Projects of this nature include microwave landing systems, area navigation systems (2D, 3D and 4D systems), the discrete address beacon system, collision avoidance systems, noise abatement procedures, all-weather landing systems, energy conservation procedures, wake vortex avoidance systems and procedures, etc. As the basis for the identification of the most critical operationally-related issues facing civil aviation, a survey and preliminary analysis of these various projects was performed to assess the potential effects of their implementation upon aircraft performance requirements and aircraft operating procedures. Additionally, the interrelated impact of these concepts on terminal area airspace design and ATC procedures was considered. Sources of data included published FAA, NASA, and contractor reports plus the wealth of information gained by the present contractor in previous investigations of terminal area operations. Also, several interviews were arranged with key personnel in the FAA's Systems Research and Development Service to learn of their most recent developments and their plans for further investigation of problems involving terminal operations. The information gained from the above sources, both the available literature and the personal discussions, was then examined to identify those programs with immediate operational impact on terminal area design.

The selected programs were then examined in greater detail to determine the factors requiring further study. The first step in this exercise involved a broad application of the concepts to terminal area operations to gain an understanding of the relative merits to be derived from implementation. This in turn led to a preliminary definition of the functional requirements for each concept and further to a specification of the tasks required to identify the input/output

parameters and the dynamics involved in the description of the concepts considered. In each case, the development of simulation models was required to gain an understanding of the parameter interactions involved, to assess the performance capabilities of specific concepts, and also to evaluate the various design tradeoffs. The results of these simulation studies were then examined to arrive at a recommended design concept for further evaluation by flight testing.

### 1.3 REPORT SUMMARY

The report of the study effort described above is organized in six sections. The following Section 2, Advanced System Concepts, describes the survey conducted to identify the specific terminal area concepts intended for further study. This section also considers the preliminary application of the selected concepts to the terminal area operations. Section 3, entitled Operational Considerations, involves a more comprehensive discussion of the benefits to be expected from implementation of the concepts considered. The development of the simulation models required for concept evaluation are discussed under Section 4, Analytical Approach, followed by Analytical Results, Section 5, in which the simulation tests conducted and results derived are presented. The last two sections relate to the considerations involved in the implementation and testing of the concepts studied. The first of these, Section 6, involves the software elements required for implementation. The second, Section 7, discusses the preliminary considerations involved in the design of specific flight tests to evaluate the proposed concepts.

The major analytical effort in this study relates to two significant aspects involved in the operation of aircraft in the terminal area. The first aspect involves the identification of requirements for and the means to execute approach paths defined by both linear and arc segments. The second aspect involves the consideration of fuel optimum flight profiles to maintain the efficient operation of aircraft arriving or departing the air terminal.

Curved approach procedures are in widespread use today as a means to achieve low noise exposure by avoiding flight over populated areas in the vicinity of the airport. All of these are flown with visual reference to obvious landmarks such as a river, a highway, or other notable ground features since current landing aids are not configured to provide active guidance along a curved approach to the airport. The classic example of one such procedure is the visual approach to runway 18 at Washington National Airport (DCA) which involves the Potomac River as a navigation reference. Unfortunately, these visual procedures are inappropriate under low visibility conditions. With the advent of the Microwave Landing System (MLS) and its broader coverage capability, current visual procedures could be extended to apply under instrument flight conditions since continuous guidance would be available through MLS along a curved approach path. The DCA River approach was selected as the principal example for further evaluation of this concept. Data was compiled from statistics on local weather observations and traffic activity to gain a relative indication of the benefits expected from the installation of an MLS facility at Washington National. From this data it was estimated that, due to inclement weather conditions, roughly 6% of the Washington-bound commercial flights are denied clearance to land. If an MLS facility were provided, then the airlines could expect to recover at least \$71K annually in lost revenue due to delays or diversions. (The latter dollar benefit is a very conservative estimate based on limited information and should not be cited as an absolute figure of merit without reference to the assumptions indicated in the text). The DCA River approach was also used as the basis for an examination of the degree of precision expected in executing this procedure with conventional autopilot designs. An approximate model of the aircraft and its guidance and control systems was developed to aid in this investigation. The model was applied to

simulate the performance of the aircraft in response to measurement biases and wind disturbances. In all of these exercises the resulting deviation from the nominal track did not exceed the accuracy requirements determined by the width of the river corridor. Also, to achieve the level of precision consistent with the accuracy afforded by MLS, it was practical to consider the means to obtain a more accurate measurement of the orientation of the aircraft velocity vector than that available from current heading sensors. A low-order nonlinear filter was examined as a means to derive velocity vector heading from MLS measurement data. The filter was synthesized and applied to estimate the heading along the DCA curved approach. The filter exhibited reasonable performance; however, improved results might be gained from further refinement of the concept. The curved approach applications study concluded with the definition of a flight experiment to be conducted at the FAA's National Aviation Facilities Experimental Center. The intent of the flight test is to evaluate the practicality of the curved approach as a means to achieve reduced noise exposure and also, in the case of the approach to runway 18 at DCA, to increase the operational efficiency at airports where unusual geographic features prohibit straight-in approaches.

As the cost of aviation fuel steadily climbs above price levels previously unimagined, greater emphasis is being applied to the development of means to reduce fuel consumption and subsequently fuel costs. Long term goals involve airframe and powerplant design modifications to optimize performance. In the near term the obvious solution to achieve reduced fuel utilization is to modify current climb, descent, and cruise procedures to minimize consumption. However, optimum flight profiles often conflict with standard operating procedures imposed by the ATC system to insure a safe and efficient flow of traffic. Also, minimum fuel does not necessarily imply minimum cost of operation. In many cases, a flight profile optimized for fuel consumption results in a time of flight greater

than that for the standard procedure. Thus the additional operating costs due to the increased flight time might offset the reduced fuel cost advantage. These and other restrictive factors were examined with relation to the energy management issue to identify candidate profile management concepts. To evaluate the energy efficiency of alternative climb, descent, and cruise procedures, an airframe/powerplant simulation model was developed on the basis of a point mass-small angle approximation. The model parameters for thrust, drag and flight path angle as well as the functional relationship for fuel flow were derived from the actual performance characteristics of a Boeing 737-200 and a McDonnell-Douglas DC-10-10. Flight profile management was achieved by controlling aircraft thrust and flight path angle. This approximate model was exercised using standard climb and descent procedures. The resulting time, distance, and fuel consumption values were consistent with the values published in the aircraft operations manuals. In all cases, the deviation between model and actual parameter values did not exceed 5%. The validated model then was applied to evaluate the relative time and fuel benefits to be derived from the utilization of six alternative vertical flight path control regimes. For the B737 no significant cost advantage was realized through the use of these modified control procedures. For the DC-10, a modest cost benefit was demonstrated for the all of the suggested control regimes. The benefits ranged from \$1.70 to \$5.20 per climb. These derived benefits were less substantial than the initial estimates; however, these figures only reflect today's fuel costs. Tomorrow's fuel costs will most likely have a more significant effect on the total cost of airline operations. The investigation of energy management concepts also concluded with the definition of a series of flight tests to validate the approximate airframe/powerplant model and to evaluate the actual benefits to be derived through the application of modified flight path control procedures.

## 2.0

## ADVANCED SYSTEM CONCEPTS

### 2.1 SURVEY ACTIVITIES

The intent of this task was to survey NASA and FAA programs and identify the concepts considered most likely to impact the operation of civil aircraft within the terminal area for at least the next ten to fifteen years. The concepts identified would then be selected for further study to evaluate the internal functional relationships, the requirements for further technology, the potential interactions between systems, and finally to design flight experiments to validate the concepts considered.

For at least the next decade the FAA is committed [References 1 and 2] to the research and development of the concepts identified as the Upgraded Third Generation (UG3RD) ATC System. Thus it was natural to begin the survey with a review of the capabilities provided in the UG3RD System to assess their potential influence on terminal area operations. The nine features of the UG3RD that were considered include:

1. Discrete Address Beacon System (DABS)
2. Intermittent Positive Control (IPC)
3. Flight Service Stations (FSS)
4. Upgraded ATC Automation
5. Airport Surface Traffic Control (ASTC)
6. Wake Vortex Avoidance System (WVAS)
7. Area Navigation (RNAV)
8. Microwave Landing System (MLS)
9. Aeronautical Satellites (AEROSAT)

It was also considered appropriate to visit and interview personnel at the Department of Transportation (FAA/SRDS and TSC) to gain the most recent information

regarding current programs and future plans. The individuals consulted included:

James Anderson, Director, Office of System Development, TSC

Robert Meier, Chief, Communications Division, FAA/SRDS

Jack Edwards, Associate Chief, Ralston Bailey and James Chadwick,  
Microwave Landing System Division, FAA/SRDS

Lawrence Langweil, Chief, Wind Shear/Wake Vortex SPO, FAA/SRDS

James Woodall, Chief, Aircraft Safety and Noise Abatement Division,  
FAA/SRDS

The most significant data gained from these interviews were the observations of the increased emphasis placed upon the prediction, detection, and alleviation of the hazardous effects due to wind shear. The recent emergence of wind shear as a top priority program was undoubtedly the result of investigations of the recent air disaster (June 24, 1975) involving a Boeing 727 on approach to New York's JFK International Airport. At the time of the interview (November 7, 1975), the wind shear program coordinated by FAA/SRDS and administered through other government agencies (NASA, DOT/TSC, National Weather Service, FAA/NAFEC) was still in the formative stage. Since that time the activity in this area has accelerated rapidly. Some of the programs involved in this effort include a study sponsored by NAFEC to develop an augmented DME to enable precise measurement of ground speed and correlate this data with observed shear conditions. NOAA's Wave Propagation Laboratory has developed a pressure-jump sensor to detect the discontinuity in barometric pressure associated with the gust fronts that typically accompany hazardous shear conditions. The laboratory has also developed a narrow-beam, vertically-aimed acoustic doppler radar capable of measuring both wind speeds and direction. The system is scheduled for demonstration at Washington Dulles later this year.

McDonnell Douglas has demonstrated on a three degree-of-freedom simulation of the DC-10 that under instrument approach conditions, coupled autopilot/ autothrottle control is more effective than manual control in responding to airspeed variations due to wind shear. This observation has inspired a study to utilize additional sensor capabilities in the event that the signal quality of the landing guidance system is below the standard required for the modes to remain coupled.

An opinion was also offered by one of the individuals interviewed that noise abatement is one of the most critical issues facing the aviation community. Unless the government, the airlines and the airframe manufacturers cooperate to take immediate steps to reduce noise, the communities surrounding major terminals will impose operational limitations which would severely restrict air travel. The two-segment approach was cited as the operational procedure with the greatest potential for noise reduction; however, it is doubtful that approval of this procedure would ever be granted due to the wake vortex issue plus resistance from the airline pilots group. Since the vortices generated by an aircraft are observed to descend at a rate of 1-1.5 m/s (3-5 ft/s), the vortex due to an aircraft on a 6° glideslope would intercept the path of a following aircraft on a shallower approach course. The observed vortex phenomena would thus favor the adoption of curved approach paths to avoid noise sensitive areas in the vicinity of the airport as well as to avoid the turbulence generated by a preceding aircraft.

Also, additional information was acquired from a meeting of the ARINC sponsored subcommittee on System Architecture and Interface (AEEC/SAI). The subcommittee was formed to develop guidelines for future avionics system design. A noteworthy statement was made at the meeting regarding energy-efficient aircraft design. It was stated that a 30% reduction in energy

consumption could be realized with modifications of the engine and airframe design, and an additional 5% reduction could be gained from a revision of the procedures involved in terminal area operations. In spite of its relative insignificance, the energy savings due to measures involving terminal operations are significant enough over the lifetime of the aircraft to warrant immediate consideration of fuel optimum takeoff, climb, descent and landing procedures. Furthermore, airframe and engine modifications are only long term solutions to the energy crisis involving only the newer aircraft. Operational/procedural revisions can have an immediate effect on the total fuel consumption of civil aviation. For example, Hughes Airwest computed fuel optimum flight profiles for each of its 250 daily DC-9 flights and, during 1973, reported a 11.4 million liter (3 million gal.) reduction in fuel consumed [Reference 3].

## 2.2 SURVEY OF UG3RD SYSTEM ELEMENTS

In this section the nine elements of the Upgraded Third Generation ATC System will be reviewed and discussed relative to anticipated civil aircraft operations within the terminal area.

DABS [References 4 and 5] is primarily intended to provide airspace surveillance, augmenting and eventually replacing the current Air Traffic Control Radar Beacon System (ATCRBS). DABS includes a high capacity, ground-air-ground digital data link which could potentially impact other terminal area systems. For example, DABS could broadcast RNAV waypoints and MLS-defined paths to approaching aircraft; DABS could also relay the MLS-derived navigation data to ATC for surveillance and approach control. However, DABS is not unique in its ability to provide a digital data link. The Digital Data Broadcast System (DDBS), recently tested at NAFEC, provides for communication of RNAV waypoints via the DME. Thus DABS itself was not considered to have, of itself, a primary impact on terminal system development. Rather the more general concept of

control message automation should be considered a supplemental subject affecting each of the primary terminal area system concepts.

IPC [References 6 and 7] involves the ground-based generation of pilot warning advisories and collision avoidance commands and the transmission of this information via the DABS data link to appropriately equipped aircraft. IPC is intended to provide proximity warning indications via traffic advisory messages to both IFR and VFR traffic, and to provide conflict protection via collision avoidance commands to primarily VFR traffic only. IPC will also serve IFR traffic as a backup to the ATC system by providing some measure of collision protection in the event of an ATC system failure. Thus IPC was regarded as a function with the greatest impact on VFR operations and, as such, was considered an element of the UG3RD outside the immediate scope of this study.

FSS modernization [Reference 8] involves the addition of automated, unattended pilot self-briefing terminals at the flight service stations. Thus this activity is inappropriate to the terminal area operational study as far as having a substantial effect on procedures or avionics complement.

Upgraded ATC automation [References 9, 10 and 11] involves, for the most part, functions performed in support of enroute traffic flow control. The exceptions include Metering and Spacing Automation and Minimum Safe Altitude Warning, both of which involve terminal area operations. The latter program is basically an independent function without considerable impact on other terminal systems. On the other hand, metering and spacing does involve several other terminal area functions. The immediate plans dictate that it (M&S) shall be implemented as part of the ARTS IIIa system. The software to accomplish M&S for a single runway has been developed and is intended for field evaluation in

late 1976. Thus metering and spacing should definitely be included in the evaluation of terminal operations. However, the subject was not considered a primary issue, since the development of a new metering and spacing concept in the context of this study was regarded as both inappropriate and impractical. Rather, metering and spacing was considered a significant factor influencing the evaluation of the primary concepts.

ASTC [Reference 12] functions relate to the provisions necessary to ensure safe and efficient movement of aircraft and vehicular traffic on the airport surface. One system under consideration enables the interrogation of individual aircraft using only the transponders required for operation with the current Air Traffic Control Radar Beacon System (ATCRBS). However, the TCV program does not involve this phase of activity and thus the subject area was not considered a prime concern at least as far as initial consideration of this study is concerned.

WVAS [Reference 13] is a program to devise the means for detecting and predicting the presence of high energy wake vortices trailing heavy aircraft at low speeds on final approach or departure. The program has entered the field demonstration phase in which acoustic and laser sensors have been installed at Chicago's O'Hare and New York's JFK airport and evaluated as alarms to warn of vortices in the approach or departure corridors. WVAS is expected to have a heavy impact on future terminal operations. When fully implemented, WVAS will enable reduced separations between aircraft on final approach, which will in turn increase airport capacity and decrease delays leading to wasted fuel. Furthermore, wake vortex and wind shear phenomena share common factors.

RNAV [References 14, 15 and 16] is a concept enabling navigation from point-to-point rather than constrained flight along radials of VOR/DME stations. Since RNAV provides more direct, hence more efficient, routing and since it

is a system in current limited use, wide spread RNAV implementation is almost assured. In the terminal area, RNAV serves as the basis for defining standard approach and departure patterns, relieving the controller of the need to issue routine radar vector commands and providing the guidance to acquire the approach and landing aid (ILS or MLS). Thus RNAV should be considered a major factor in future terminal area operations.

MLS [References 17, 18 and 19] is the navigation signal source intended to provide broad coverage for precise approach and landing guidance. A reduction in noise impact should be realized with MLS since the expanded coverage will permit multiple glideslopes and curved approaches to avoid noise sensitive areas in the vicinity of the airport. Further, the accuracy provide by MLS will theoretically enable tighter control of aircraft within the terminal area to increase runway utilization. These considerations, together with the fact that the ICAO demonstration of MLS is a principal goal of the TCV program, dictate that MLS be regarded as a major study factor.

AEROSAT is a study program to determine the potential for satellite surveillance in the ATC system. Although AEROSAT is primarily intended for oceanic coverage, it is not expected that terminal area navigation and control through satellites will emerge as a major factor during the period under study.

### 2.3 FAA TOP TEN PROGRAMS

Another basis for selection was the publication of a list by the Office of the Administrator identifying the ten high priority FAA programs. These ten programs will receive principal attention and will be assigned completion dates and specific FAA offices accountable for their accomplishment. The ten programs, all identified as equally important, are:

1. DOT Secretary's Task Force Report (19 safety recommendations)
2. FSS Modernization

3. Concorde
4. New York Common IFR (new)
5. Engine Retrofit for Noise Reduction
6. National Noise Policy
7. Wind Shear
8. Automation
  - Minimum Safe Altitude Warning
  - Conflict Alert
  - Flow Control
  - Metering and Spacing
9. Post Crash Survivability
10. Collision Avoidance System

Of the ten programs identified, only the wind shear, automation, and collision avoidance studies relate directly to terminal area operations in the sense that they would impact immediate considerations.

#### 2.4 SUGGESTED STUDY ITEMS

As a result of the survey activities previously described, three specific study areas were initially identified as having a major potential impact on terminal area operations. The three study items deemed appropriate for further investigation include:

1. RNAV/MLS - to consider the requirements and the means for achieving curved approaches using MLS; also, to examine the RNAV to MLS transition procedures consistent with operational and avionics limitations.
2. Energy Management - to identify factors influencing energy efficiency and apply results to propose fuel optimum measures satisfying ATC and environmental factors.
3. Wind Shear/Wake Vortex - to examine general aspects of shear and vortex phenomena and to consider hardware and software requirements to reduce hazards.

The three study categories indicated above are discussed further with regard to factors considered in evaluating the requirements for further study.

#### 2.4.1 RNAV/MLS

The first issue addressed was the consideration of the requirements for, and the means of implementing, curved approach paths in the terminal area. One of the overriding factors influencing the demands for curved approach paths is the noise abatement issue. Guidance along curved or segmented approaches could be provided by MLS to extend the use of current VFR noise-abatement procedures to periods when weather conditions dictate the use of IFR operating procedures. For example, the Canarsie approach to Runways 13R and 13L at JFK (Figure 2.1) involves an initial flight path coincident with the 041° radial of the Canarsie VOR to a point 7.4 Km (4 nm) from the threshold, where a sequence of lights direct a 90° turn to intercept the final approach. The approach to 13R is a VFR procedure [305 m (1000 ft) and 5.6 Km (3 nm)], while the added distance [1.85 Km (1 nm)] involved in the turn to approach on 13L renders this procedure marginally IFR [244 m (800 ft) and 3.7 Km (2 nm)]. Both approaches afford relatively low noise exposure to densely populated districts, since they primarily overlay the uninhabited marshlands of Jamaica Bay. However, the ILS approach to 13L (Figure 2.2) is considered a noise sensitive profile since it involves an initial approach segment that parallels the Brooklyn shoreline and a 90° turn to intercept the localizer beam 16.7 Km (9 nm) from the threshold. The final approach leg involves a flight path over the densely populated areas of Long Island. With MLS providing coverage within a 40° sector either side of the extended runway centerline, the low-noise Canarsie approach could be utilized under IFR conditions with continuous MLS guidance available from the Canarsie station location to touchdown.

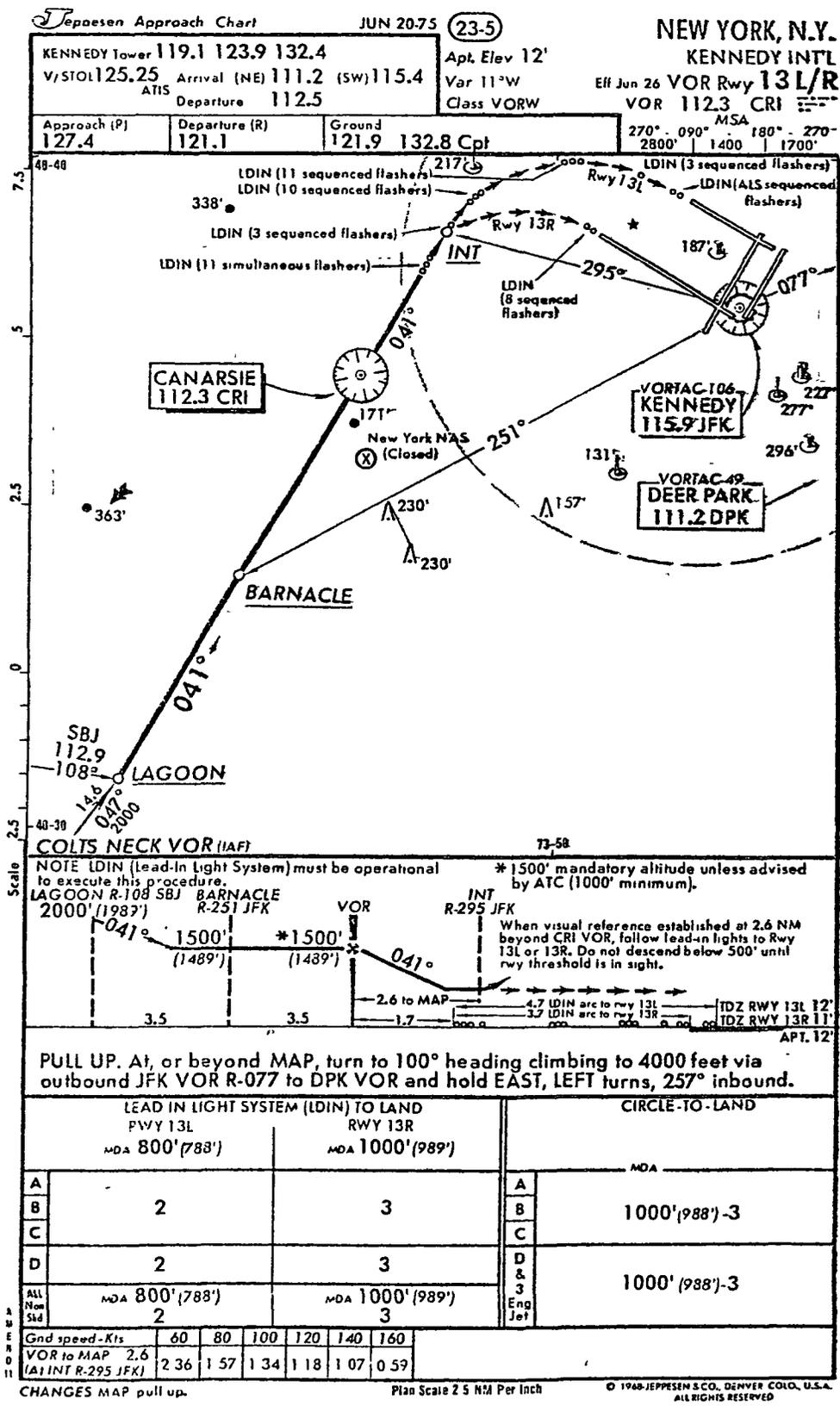


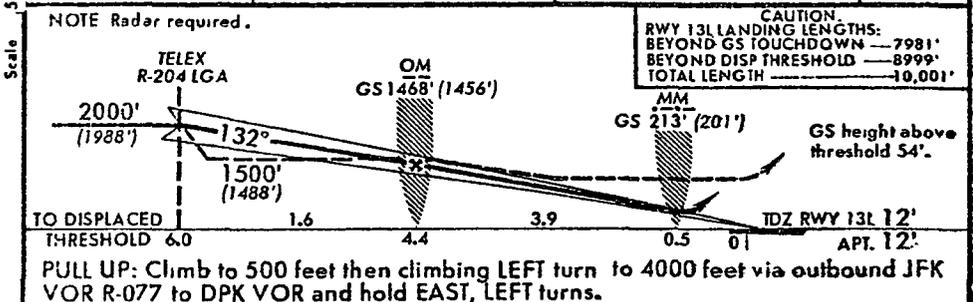
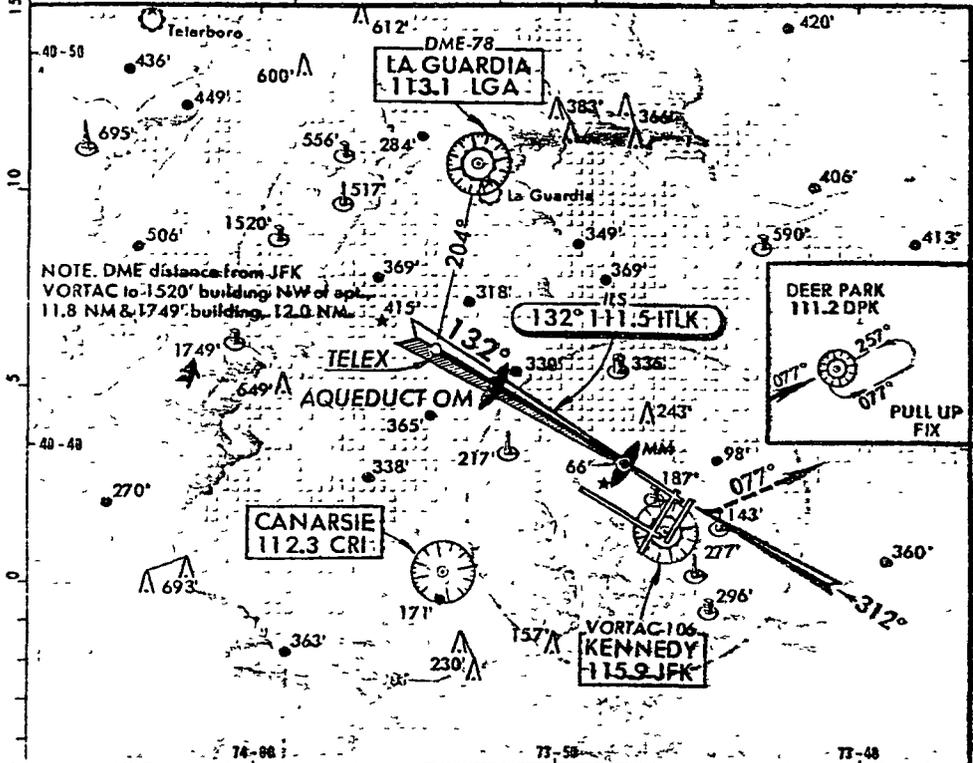
Figure 2.1 Canarsie Visual Approach to JFK - Runway 13L/R

KENNEDY Tower 119.1 123.9 132.4  
 V/STOL 125.25 ATIS Arrival (NE) 111.2 (SW) 115.4  
 Departure 112.5

Apt. Elev 12'  
 Var 11°W  
 GS 332.9

KENNEDY INT'L  
 ILS Rwy 13L  
 LOC 111.5 IILK

Approach (R) 127.4  
 Departure (R) 121.1  
 Ground 121.9  
 132.8 Cpt



STRAIGHT-IN LANDING RWY 13L							CIRCLE-TO-LAND	
DH 212' (200')		DH 262' (250')			MDA 580' (568')		MDA	
FULL ILS		Mtr out	ALS out	Mtr & ALS out	GS out	GS & MM out	GS & ALS out	GS, ALS & MM out
A	1/2	1/2	3/4	1	1/2	1	580' (568') -1	
B	1/2	1/2	3/4	1	1/2	1	580' (568') -1 1/2	
C	1/2	1/2	3/4	1	1/2	1	600' (588') -2	
D	1/2	1/2	3/4	1	1/2	1	680' (668') -2	
All Non Std	DH 362' (350') 3/4	DH 362' (350') 1			MDA 580' (568') A, B, C, D 1/4		Non-Std 680' (668') -2	
Grnd speed - Kts	60	80	100	120	140	160	Air Carrier Jets SFL or HIRL out-not less than 3/4.	
C.S	3 00"	318	424	530	636	742	848	
OM to MAP	4.4	4.24	3.18	2.38	2.12	1.53	1.39	

CHANGES FAF, LOC altitude at OM, MAP. © 1973 JEPPESEN & CO., DENVER, CO., U.S.A. ALL RIGHTS RESERVED

Figure 2.2 ILS Approach to JFK - Runway 13L

Another curved approach candidate is the visual River approach to Washington National (Figure 2.3). Primarily intended as an obstacle clearance and security measure, the procedure also serves to minimize the noise impact by concentrating the noise over the Potomac. The procedure is definitely a visual approach, applicable whenever the ceiling and visibility are at least 1067 m (3500 ft) and 5.6 Km (3 nm). The procedure is initiated after direction is provided by radar vectors to a point 18.5 Km (10 nm) northwest of the terminal at an altitude of 914 m (3000 ft), whereupon the aircraft visually follows the river to land on runway 18. With an MLS lateral coverage capability of 60°, approach guidance would be provided over the entire flight path; with a 40° MLS sweep sector, less than 10% of the initial track would be outside the coverage sector. In comparison with the 90° turn to final involved in the Canarsie approach to JFK International discussed previously, the sequence of turns required to track the course of the river is far more complex and demanding as far as automatic guidance system capability is concerned. Thus the latter approach was selected for further study and the requirements for executing this procedure using MLS are discussed in greater detail in succeeding sections of this report.

The second issue considered within this study category involves the transition on approach from the region of VOR/DME (RNAV) coverage to the region of MLS coverage. Under worst case conditions the cross track deviation between the RNAV and MLS defined flight paths may exceed 2.8 Km (1.5 nm) [Reference 20]. However, in the usual case where the navaid is located within the vicinity of the terminal area, the deviation is not expected to exceed .9 Km (0.5 nm). In the worst case, the nearly-instantaneous step change in the error signal to the autopilot could induce unacceptably large corrective maneuvers annoying to the passengers, the flight crew and the controller in charge of maintaining

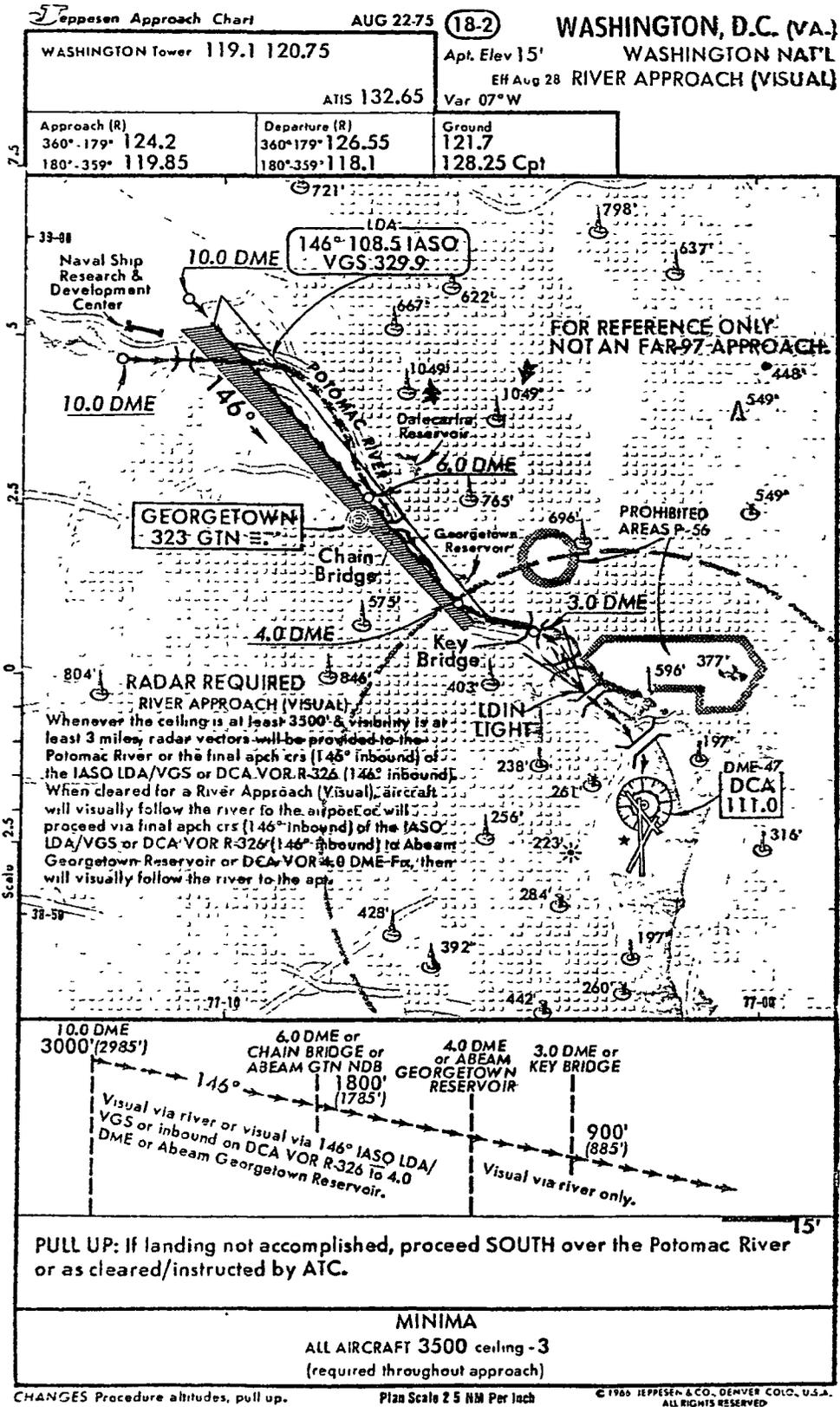


Figure 2.3 Visual River Approach to DCA - Runway 18

surveillance. To avoid this possibility and also to insure that the transition does not interfere with other approach control functions, it is appropriate to consider the means to effect the transition from RNAV to MLS signal coverage.

The consideration of appropriate transition maneuvers involves the characterization of typical approach patterns intersecting the MLS coverage boundary. The point of intersection will depend upon the extent of MLS coverage, the design of the terminal route structure and the particular approach under consideration. Typical transition characterizations include the interception of MLS coverage on the downwind leg 9.3 Km (5 nm) from the turn waypoint or, on a straight-in approach, 37.0 Km (20 nm) from the threshold. For interception on the downwind leg, three possible lateral maneuvers have been suggested [Reference 16] for transition to MLS navigation data. These are:

- A. Utilize MLS guidance information to execute an immediate course correction to intercept the MLS-defined approach path, i.e., the downwind leg.
- B. Utilize MLS guidance information to define a flight path intercepting the MLS-defined approach path at the next waypoint, i.e., the base leg turning waypoint.
- C. Utilize MLS guidance information to define more accurately the next approach segment, i.e., the base leg. Also, utilize MLS to establish and execute the transition maneuver to intercept the following segment and employ VOR/DME guidance along the current segment.

Also, the objective of another independent phase of this study was to develop a transition algorithm for inclusion in the TCV research aircraft. The results of this effort (to be reported in a separate volume of the final report) is an algorithm involving the following procedure:

- D. Utilize MLS guidance information to establish a more accurate estimate of current position. Also, utilize MLS to define and execute a maneuver sequence consisting of an initial straight line segment, an intermediate arc segment, and a final straight line segment to intercept the extended runway centerline at the final approach fix.

In comparing these transition possibilities, several factors should be considered. These include:

- Passenger Comfort - Passengers are responsive to attitude, attitude rates, and accelerations when visual conditions exist, and only to accelerations during instrument conditions [Reference 21]. Experience indicates that deck angles much greater than 15 degrees (pitch-up only) cause passengers to become uneasy and complain. Also, normal accelerations in excess of 0.1g are not favorably accepted. However, passengers are not critically sensitive to bank angle, which is limited more by physical considerations and the procedures preferred by pilots. Of the four maneuvers considered, Procedure A affords the greatest potential for discomfort. If the aircraft intercepted the MLS coverage sector in the immediate vicinity of the base leg turn waypoint, the rapid sequence of maneuvers to correct for the signal discontinuity and to execute the turn to the following segment could result in a situation disconcerting to the passengers. On a relative scale, Procedure D is probably the least sensitive in this respect, since the maneuvers involved are very gradual. However, in a general sense, the issue could be considered insignificant, since the design constraints imposed on the autopilot are such as to limit correction commands within reasonable limits.

- Pilot Reaction - This and the preceding criteria are similar in the sense that the execution of the transition maneuver should not result in any alarming reaction. Thus the judgments applied in the above discussion also pertain to this criteria. Should the commanded maneuver be considered too abrupt, an alerting annunciation could be provided to the pilot in advance of the transition.
- ATC Response - The maneuver at RNAV/MLS transition should not alarm the controller monitoring the approach. In his surveillance role, the controller is charged with the responsibility of assuring that all aircraft with his sector maintain their assigned tracks. Thus any unexpectedly large deviation from the approach pattern would conflict with the controller's task of maintaining a safe and orderly flow of traffic in the terminal area. In this respect, Procedure D is the most objectionable corrective maneuver from the controller's standpoint, since an aircraft's flight path from the point at which it penetrated the MLS coverage sector to the final approach fix is largely dependent on the aircraft's estimated position at the point of transition from RNAV to MLS. On the other hand, Procedure A is least objectionable, since an immediate correction is made to return the aircraft to the intended track.
- Implementation - Procedure A is probably the most attractive concept in this respect since, from an operational viewpoint, MLS is regarded in the same sense as any other navigation signal source. The computational requirements are roughly equivalent to those involved in the transition from one VOR/DME station to another. Procedure C is probably the most complex transition method to implement since it involves the operational considerations inherent in any beam or segment capture situation.
- Delivery Control - The transition method should not adversely affect the sequencing, spacing, and time control functions of the ATC system.

The metering function is assumed to apply outside the coverage area of MLS. In terms of time control, Procedure D offers the greatest flexibility since the computation of the flight path could consider the estimated time of arrival at the final approach fix to achieve an ordered sequence of arrivals. However, this same procedure is less effective in achieving proper spacing, since, as previously discussed, path definition is an autonomous function. In this respect Procedure A is more attractive.

The preceding subjective evaluation of the four RNAV to MLS transition procedures is summarized in Table 2.1, where each method is ordered in terms of its acceptability within a given evaluation category, i.e., a rating of 1 is most desirable, a rating of 4 is least desirable.

Table 2.1 Ranking of RNAV/MLS Transition Procedures

RNAV/MLS Transition Procedure	A	B	C	D
Passenger Comfort	4	3	2	1
Pilot Reaction	4	3	2	1
ATC Response	1	2	3	4
Implementation	1	3	4	2
Delivery Control	1	3	4	2

This exercise indicates that Procedures A and D are roughly comparable as suitable means to accomplish the transition from RNAV to MLS signal reception. The selection of one or the other is dependent on the dominant consideration. Should the concern of passenger and pilot reactions dominate, then Procedure D would be the logical choice. Should compatibility with the existing ATC structure be the primary concern, then Procedure A would best fulfill this requirement.

#### 2.4.2 Energy Management Concepts

Since the beginning of the energy crisis in 1974, there has been an increased awareness of the desirability of energy conservation on the part of aircraft operators. Increased fuel costs have contributed significantly to increases in direct operating costs for civil turbojet aircraft. Consequently, procedures which save small amounts of fuel per operation can accumulate to relatively large savings when integrated over a year's time. At the present time most civil turbojet powered aircraft are equipped with similar flight instruments, which are used to govern the vertical profile of the aircraft. These conventional flight instruments measure indicated airspeed, Mach number, altitude and rate of climb. The sensors are connected to a flight director and/or an autopilot to control the aircraft vertical profile either manually or automatically, respectively. The use of this conventional instrumentation at various speed or rate of climb settings produces vertical aircraft profiles which require varying amounts of fuel and time to fly. Many of these types of aircraft will be flying in the National Airspace System for a number of years to come. An investigation of alternate techniques for climbing and descending these aircraft using either the conventional instrumentation or modifications to this instrumentation could identify aircraft profiles with significant fuel savings. Consequently, an investigation of energy saving techniques for climbing and descending civil turbojet powered aircraft was initiated.

##### 2.4.2.1 Merits of Specific Climb/Descent Profiles

Aircraft climb profiles are often placed in one of two categories. The first is the high speed climb profile. In the high speed climb the aircraft throttle setting is placed in the normal-rated power position and the elevator is trimmed to produce a specified airspeed or Mach number, which is near the

high speed performance limits of the aircraft. This climb procedure produces flight profiles which are generally time efficient but energy inefficient. The nature of the profile is such that the aircraft spends a longer period of time in high speed, low altitude, high drag conditions. The other type of climb profile is known as the long range climb. Again the throttle is placed in the normal-rated power setting but the airspeed is held at a lower value than in the high speed climb. The slower speed results in a steeper flight path angle and lower drag which results in a longer flight time at the higher altitudes where air density and drag are lower. However, the slower airspeeds generally produce longer total flight times and increased cost of operations for those costs which are sensitive to flight time, such as crew cost, aircraft maintenance and inspection costs.

Aircraft descent profiles can also be divided into high speed and long range descent. Again the high speed descent is time efficient but not necessarily fuel efficient. The high speed descent is initiated by placing the throttle in the flight-idle position and adjusting the elevator trim to produce an airspeed which is at or near the performance limits of the aircraft. The long range descent is also flown at flight-idle but the aircraft is first permitted to decelerate at level altitude until a prescribed airspeed, which is well below maximum, is reached and then the aircraft is trimmed to descend at the specified airspeed. Due to the slower airspeed the long range descent takes a considerably longer total time to descend than does the high speed descent. In recent years, some aircraft have been equipped with navigation computers which permit the aircraft to descend at a specified flight path angle. These navigation computers are known as 3D-RNAV or VNAV computers. The VNAV computer helps the pilot to identify the top of descent point, which permits him to have more control over the descent and to null out variations in the spatial flight path due to wind

and other environmental affects. The VNAV computer also helps the pilot to remove the uncertainty involved in identifying the time and place at which descent should begin. The VNAV descent may be made in either a partial power mode where airspeed and descent gradient are maintained or at flight idle where the profile is maintained but the aircraft speed is permitted to vary within some operating limits which are based on aircraft control and flight safety.

#### 2.4.2.2 Procedures to Implement Optimum Paths

At least two possible approaches to aircraft profile optimization are feasible. The first approach involves instrumenting the aircraft in such a manner so as to be able to determine the optimum profile by sensing the environment and the state of the aircraft and processing these inputs through some optimization algorithm to predict the optimum profile. The aircraft control system is also reconfigured to permit the aircraft to follow the optimum energy profile as defined by the prediction algorithm. The second approach to the problem involves an a priori determination of the optimum profile based upon weather reports and the aircraft weight and stage length. The aircraft flight control system is then modified in such a manner so as to permit the aircraft to follow the predetermined optimum profile. For the purposes of this program the second approach was taken. This approach was followed for two principal reasons. First, a number of civilian turbojet aircraft contain the types of speed and altitude sensors which are compatible with the following of a predetermined profile. The modifications necessary to the flight control system which would permit an aircraft to follow an optimal energy profile would thus be considerably less demanding from a retrofit standpoint. Consequently, this approach could be utilized on a large number of existing aircraft at a lower cost than that required by the first approach. The second reason for

choosing this approach is that it provides a natural first step in defining the instrumentation needs for the fully instrumented aircraft that was described in the first approach. For example, under flight test conditions, should the achieved performance and measured temperature both deviate significantly from the predicted performance figure and the predetermined temperature curve, then it is reasonable to assume that fuel efficiency is sensitive to temperature changes and should thus be included in any real-time optimization algorithm.

Because of the approach taken, the investigation was limited to studying those profiles that are attainable by conventional flight instrumentation, that is, indicated airspeed, Mach number, rate of climb/descent, altimetry, and navigation equipment such as the VNAV computer which may be driven by a wide variety of input sensors ranging from VOR/DME to INS and Doppler systems. The aircraft are considered to fly standard type profiles such as constant indicated airspeed or constant Mach number with the transition between control modes occurring at specified altitudes, airspeeds or Mach numbers. In addition, some aircraft acceleration/deceleration control modes are included which are based on the conventional flight instrumentation. These control modes involve keeping a constant ratio of changes in airspeed to changes in height or changes in Mach number to changes in height as the aircraft climbs or descends.

It is felt that in taking this approach a large number of aircraft which are presently in the civil fleet could make use of these procedures. In this manner an early, yet substantial, impact upon energy conservation could be achieved through a minimum of retrofit equipment purchases or aircraft replacements.

#### 2.4.3. Wind Shear

This third study category initially considered for further investigation involves the phenomenon of wind shear, characterized by changes in wind

direction or velocity over short time periods. This of course, can have disturbing, or even serious effects on aircraft operations during critical periods of flight, especially the final approach phase. The most serious occurrences are the result of significant changes in the headwind component. If the headwind component drops rapidly during approach, descent rate will increase at a corresponding rate even if sufficient airspeed margin over stall speed is maintained. If the aircraft is near obstructions at this time, a hazardous condition results. If the change in headwind component results in an airspeed at or below stall, catastrophic results are certain if insufficient altitude remains for recovery. Due to recent wind shear-induced incidents, research is being conducted into means of predicting, through meteorological observations, and detecting, through acoustic and laser sensors, wind shear presence from ground observations. Additional attention is due to the problem of sensing, avoiding, and successfully flying through wind shear conditions using self-contained airborne capabilities.

Serious wind shear most often accompanies gust fronts associated with thunderstorms. These fronts precede the storms by as much as ten miles. Other causes are the movement of cold and warm fronts, particularly if the frontal movement is quite rapid. Low level wind shear conditions are most likely to occur when the frontal temperature difference exceeds  $10^{\circ}$  F and/or when the front is moving at thirty knots or more. The detection of such frontal or thunderstorm conditions through meteorological observations is a useful method of predicting potential shear conditions. Acoustic and laser sensors developed for detection and tracking of wake vortex phenomena can be applied to the task of detecting wind shear conditions along approach or departure paths in real time for traffic control purposes. There remains however, the problem of detecting, and doing something about, wind shear from the airborne point of view.

There are two basic approaches to on-board wind shear detection and measurement: (1) detection at the location of the aircraft, and (2) detection in advance of the aircraft along the intended path. The first approach is perhaps more easily implemented, but is lacking in providing timely information. The second approach would provide predictive information, but probably with a lower accuracy and at a greater expense. Local detection at the aircraft could be provided through several combinations of available or new sensors. Theoretically, such sensors could be integrated with a control/display system which would cause (or indicate to the flight crew) certain actions to be initiated to minimize the effect of the wind shear. Predictive detection could be used in order to avoid wind shear effects altogether, or to allow compensation actions to be initiated in advance of the wind shear encounter.

Sensors available for use in a local wind shear detection system include compass, air data (airspeed, altitude, rate of climb), stall warning, ILS/DME, and for aircraft so equipped, angle of attack sensors, INS systems, precision RNAV systems (such as dual DME systems), and MLS systems. Additionally, pitch attitude gyros may be useful. The major function of a local shear detection system is to detect the headwind component. This can be done by comparing measured true airspeed from the air data system with inertial groundspeed, or groundspeed derived from some precision navigation system as a reference. Abrupt changes in headwind could therefore be easily detected. Other data sources, such as rate of climb, attack angle and attitude, could be used in a more complex wind shear detection and evaluation system which could evaluate the effect of changing winds on aircraft performance.

The potential sensors which could be used for advanced detection of wind shear conditions include sensors similar to those used in the ground-based shear/vortex detection systems, namely, laser and acoustic doppler sensors. Naturally, considerable development would be required to adapt them to airborne use.

Another consideration is the automatic reconfiguration of the aircraft to minimize the hazardous effects of wind shear on approach. The most obvious possibility is the inclusion of an automatic throttle control to maintain airspeed; however, the slow response time of the typical turbine engine might discourage the application of this approach in quick reaction situations. It might be more appropriate as a preventative procedure to be used in the event of impending wind shear. Another configuration change involves the deployment of flaps to gain the lift lost as a result of the decreased airspeed. Again, this approach does not provide a quick response to the reduced performance during wind shear. A third possibility is to deliberately degrade performance by extending the spoilers to increase drag and increasing the thrust to compensate. Then, in the event that wind shear were encountered, the spoilers would be retracted to effect an almost instantaneous decrease in the drag to overcome the effects of reduced airspeed.

Although the wind shear issue was identified as a critical research area, early in the study it was decided to deemphasize this aspect of the study and concentrate on the RNAV/MLS and energy management subjects. The decision was based on the realization that the activity in wind shear was accelerating at such a rapid rate that a considerable expenditure of time and project funds would have been required to keep pace with the evolving technology. Thus the attention to current wind shear developments would have precluded the possibility of any contribution of greater significance than that anticipated from more heavily funded studies dedicated solely to the study of wind shear phenomena.

## 2.5 SUMMARY OF SECTION 2

Based on a survey of current literature and discussions with informed personnel at the FAA, three study categories were initially identified as major factors influencing the development of new equipment and the consideration of revised ATC procedures to serve the anticipated requirements for air carrier

operations within the terminal area. The three study items intended for further investigation involved the consideration of the RNAV/MLS transition and MLS curved approaches, the consideration of energy efficient climb and descent procedures, and the consideration of wind shear detection and alleviation. However, it was recognized that further pursuit of the wind shear topic would require a more extensive survey of current activities than was practical. Thus at the conclusion of the phase involving the survey of advanced system concepts it was decided to focus attention on the identification of curved approach applications possible with MLS and also on energy management procedures involving advanced vertical flight path control concepts. The principal intent of the first study objective was to consider the potential for curved approach paths and to identify the modifications of current avionics components and operational procedures required to accomplish this objective. For the energy management study, the primary goal was to compare alternative climb and descent procedures to gain a realistic assessment of the relative benefits to be derived from energy efficient control concepts.

In regard to the RNAV to MLS transition maneuver four alternative procedures were reviewed and compared with respect to the factors affecting the passengers, the flight crew, and the ATC controller as well as the requirements for implementation. This exercise demonstrated a preference for two of the four alternatives. The one preferred approach involves an immediate return to the MLS-defined track; the other involves a sequence of linear and arc segments utilizing MLS guidance to intercept the final approach segment at the outer marker. With respect to curved approach applications with MLS coverage, several visual noise abatement procedures were cited as candidate profiles to be exercised under IFR conditions with active guidance provided by MLS. One of these, the visual River approach to Washington National, involves the most complex maneuver

sequence and was thus selected as the baseline example for further consideration of the impact of curved approach implementation on the design of avionics components and ATC procedure specification. Also, the issue of energy management concepts was introduced and several alternative climb and descent profiles were reviewed and compared. The rationale for initially considering only open loop control methods for flight profile management was presented.

### 3.0

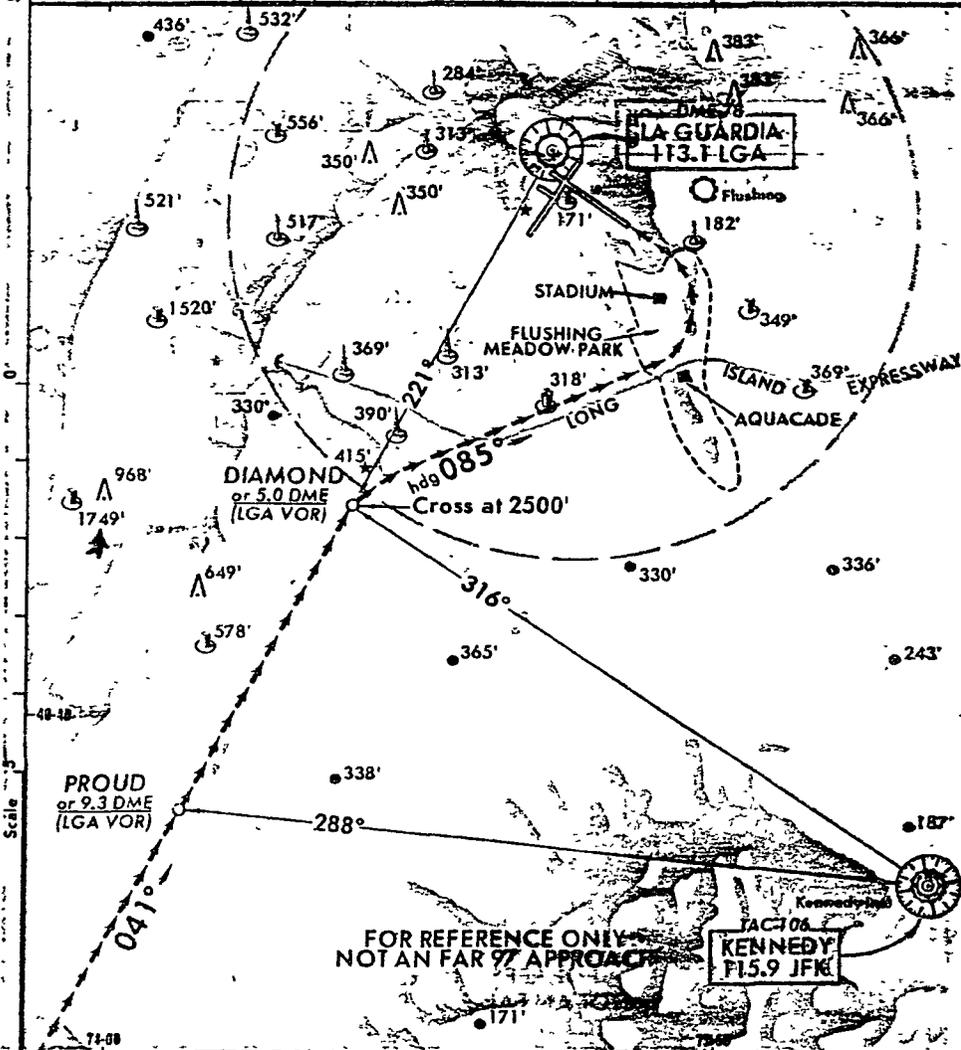
## OPERATIONAL IMPACT

### 3.1 MLS GUIDANCE APPLICATIONS

The increased navigation capability provided by MLS in the terminal area affords greater flexibility in designing approach paths to meet specific operational advantages currently unavailable with ILS. As previously discussed, the wider coverage available with MLS enables guidance along curved approach paths to avoid noise sensitive areas within the vicinity of the terminal. Presently, curved approach procedures are utilized to minimize the impact of noise in these sensitive areas; however, the procedures usually require the use of geographic features to provide visual reference on approach. The two specific cases cited earlier are prime examples; the Canarsie approach to JFK International, involving the sequence of lead-in lights to direct the 90° turn to final; and the River approach to Washington National, involving the Potomac River as a visual reference. Still other examples are the LaGuardia Expressway Approach to runway 31 and the Delaware River Approach to Philadelphia. The LaGuardia (Figure 3.1) approach procedure directs that STET aircraft cross the Diamond Intersection at 762 m (2500 ft), turn east on a 85° heading to intercept and follow the Long Island Expressway for 5.6 Km (3 nm), then execute a 135° turn to intercept the final approach path less than 3.7 Km (2nm) from the threshold of runway 31. The procedure serves to concentrate the noise over the expressway, where the level of ambient noise due to highway traffic approaches the level of disturbance due to arriving aircraft, and also over Flushing Meadow Park on the fringe of a high density residential district. The Philadelphia approach procedure over the Delaware River (Figure 3.2), like the Potomac River approach to DCA, serves to focus the noise over a body of water and thus minimize the disturbance effect. These are but a few of the ever increasing number of noise abatement procedures specified by local airport

LA GUARDIA Tower 118.7 119.95 Apt. Elev 22'  
 ATIS Arrival 113.1 125.95 EXPRESSWAY APPROACH (VISUAL) Rwy 31  
 Departure 113.1 Var 12°W

Approach (P) 118.0	Departure (R) 120.4	Ground 121.7 135.2 Cpt
-----------------------	------------------------	------------------------------



**EXPRESSWAY APPROACH (VISUAL) RWY 31**

This approach may be utilized when ceiling is 3000 feet and visibility 5 miles or better.

When cleared for an Expressway Approach to Runway 31 (while on the La Guardia VOR/DME 221° Radial), cross Diamond Intersection or 5.0 DME at 2500 feet. Turn right at Diamond, heading 085° and descend to Runway 31 via the Long Island Expressway and Flushing Meadow Park.

**MINIMA**  
 3000 ceiling-5

CHANGES Prospect Int renamed Proud. Plan Scale 2.5 NM Per Inch © 1975 JEPPESEN SANDERSON, INC., DENVER, COLO., U.S.A. ALL RIGHTS RESERVED

Figure 3.1 Expressway Approach to LGA - Runway 31

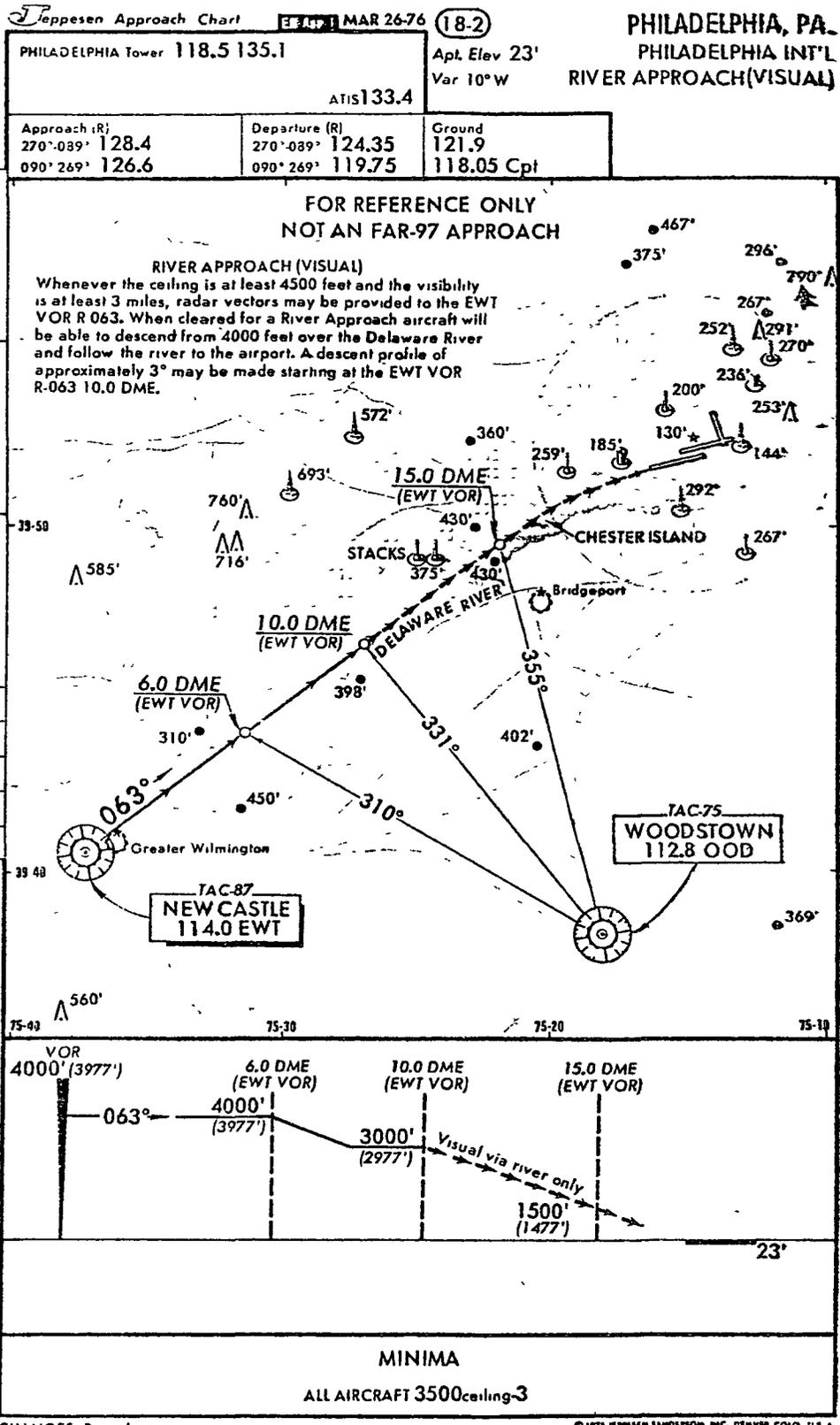


Figure 3.2 Visual River Approach to PHL - Runway 9R

commissions in an attempt to quiet the protests of residents in the vicinity of municipal airports.

Unfortunately the majority of these noise abatement procedures are applicable only under conditions when visual flight rules apply. Since most of these involve the use of local ground features to provide visual reference, they must be abandoned in favor of instrument flight procedures whenever the prevailing visibility and ceiling are below the expressed minimums for each specific visual approach. In those situations dictating instrument procedures, the ground tracks of approaching aircraft most likely cover populated areas in the vicinity of the airport since a straight-in approach path aligned with the extended runway centerline is normally required from the outer marker (about 6 miles from the runway threshold) to touchdown. At the outer marker, the aircraft is below 609.6 m (2000 ft), the level at which the noise perceived on the ground is above the noise annoyance threshold (75 dBA).

Consider, as an example, the Washington National Airport where jet aircraft operations are confined to runways 18 and 36. An ILS glideslope and localizer beacon provide guidance on approaches from the south to runway 36; however, no localizer coverage is available on runway 18 since a straight-in approach would violate the restricted area enclosing the Capitol, the White House, and the various Federal Government buildings. There are three possible approaches to runway 18; the Potomac River approach previously mentioned, an instrument approach utilizing a localizer type directional aid (LDA), and a VOR/DME approach with step-down fixes to maintain clearance of obstacles within the vicinity of the flight path. The LDA approach (Figure 3.3) involves a localizer type beacon coincident with the 140° radial of the DCA VORTAC sited adjacent to the runway 18 threshold. Vertical guidance is provided by standard glideslope equipment and is paired in frequency with the localizer. The published

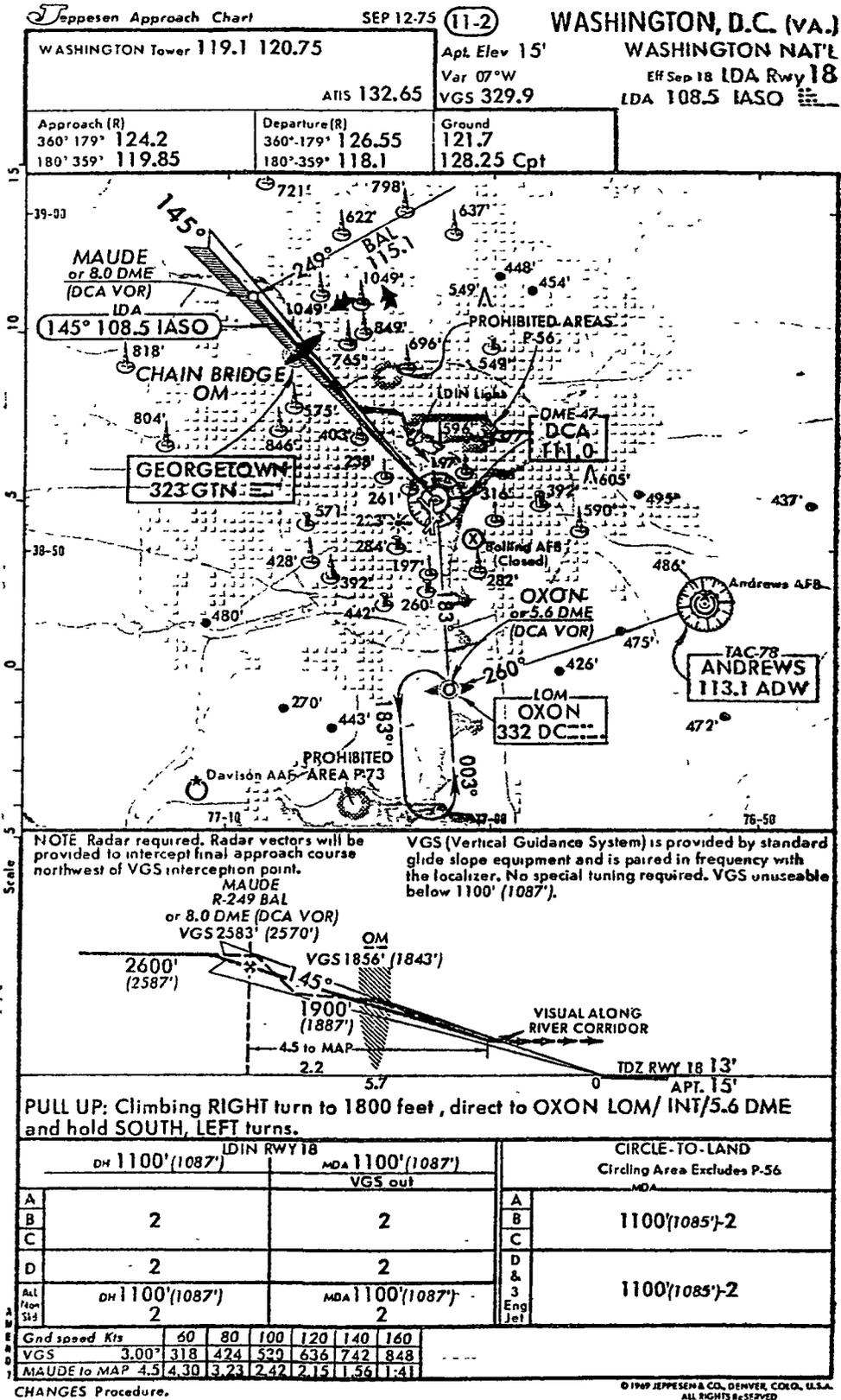


Figure 3.3 Localizer-Type Approach to DCA - Runway 18

minimums [3.7 Km (2 nm) and 2037 m (1100 ft)] are higher than those for the ILS approach to runway 36, since vertical guidance is unuseable below 2037 m (1100 ft). The procedure directs that at the missed approach point where the ground track intersects the Potomac River, the flight path shall deviate from the localizer - defined course and follow the visual approach along the river corridor. The noise impact of this approach is minimal since a major portion of the track is coincident with the Potomac River. The maximum deviation of the ground track from the river's course is over the parklands adjacent to the George Washington Memorial Parkway where the population density is low. The VOR/DME procedure (Figure 3.4) is a straight-in approach along the 153° DCA VORTAC radial with a final 27° turn to align the flight path with the runway centerline. The procedure includes step-down fixes to insure that the approaching aircraft clears obstacles in the immediate vicinity of the nominal flight path. The minimums are 1.9 Km (1 nm) and 219 m (720 ft). The noise impact for this approach is undoubtedly more severe than that for either of the two preceding approaches to runway 18, since the segment of the flight path south of the Key Bridge is immediately over [less than 274 m (900 ft)] the densely populated residential district of Arlington.

With regard to approach utilization, the visual procedure over the river corridor is by far the most frequently used approach whenever the wind is out of the southern sector. From surface weather data accumulated over a five year period at the Washington National Airport [Reference 22] it was estimated that, on an hourly observation basis, the ceiling and visibility were greater than 1067 m (3500 ft) and 5.6 Km (3 nm), 84% of the time. This information was gained from a compilation of monthly reports of weather observations (Table 3.1). The percentage figure correlates fairly well with reported traffic activity at Washington National [Reference 23]. During 1974, 202,759

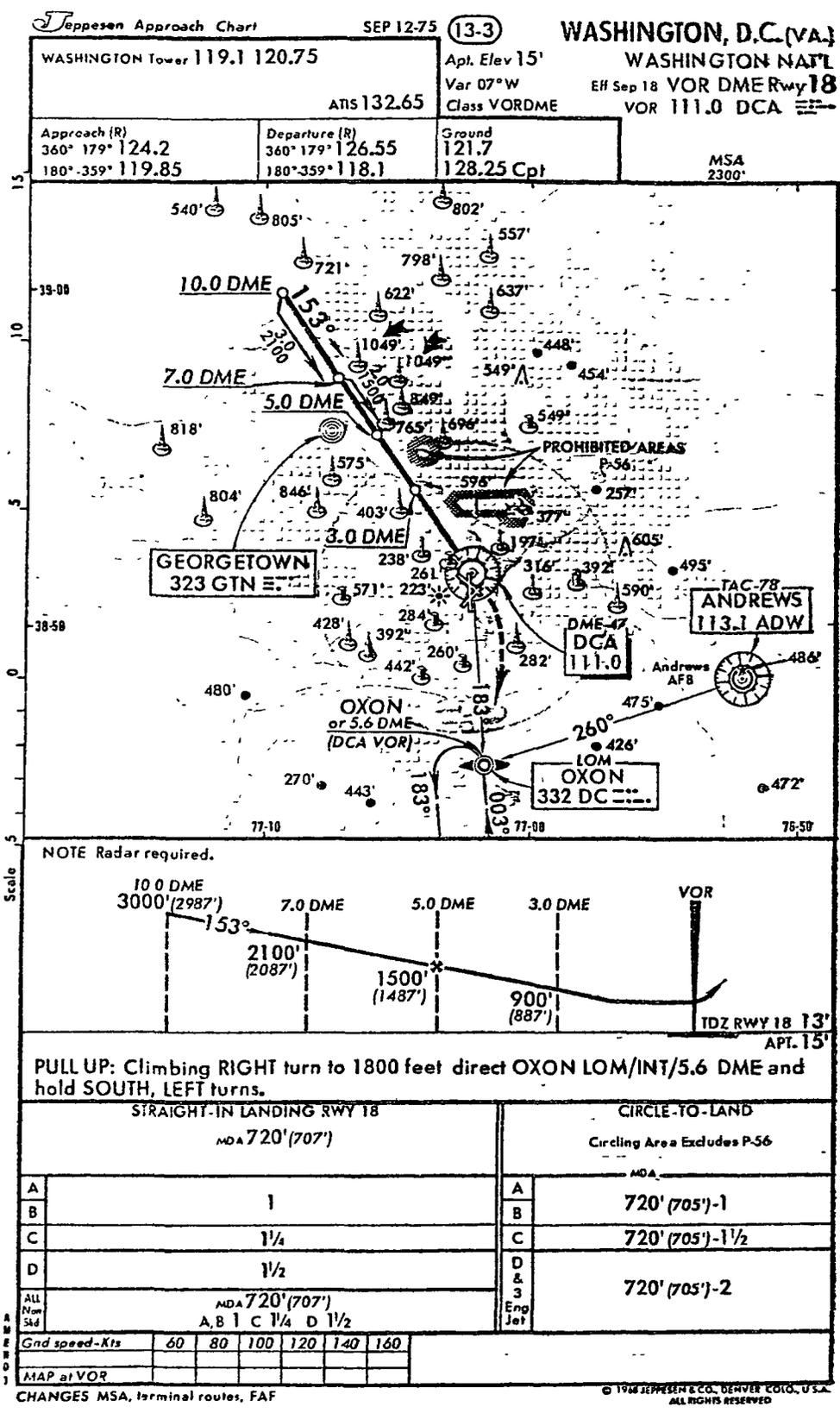


Figure 3.4 VOR/DME Approach to DCA - Runway 18

VISIBILITY		CEILING (M)										TOT.
		0	30.5-61.0	91.5-121.9	152.4-274.3	304.8-579.1	609.6-883.9	914.4-1493.5	1524.0-2895.6	over 2895.6		
KM	NM	0	100-200	300-400	500-900	1000-1900	2000-2900	3000-4900	5000-9500	over 9500		
0 - 23	0 - 1/8	+								+	+	
35 - .69	3/16 - 3/8	+		+						+	+	
93 - 1.39	1/2 - 3/4	+		+					+	+	1	
1.85 - 4.63	1 - 2-1/2	+		1	2	+		+		2	5	
5.56 - 11.1	3 - 6			+	2	2	1	1	2	9	18	
13.0 - 29.6	7-16				1	2	1	4	9	59	76	
37.0 - 55.6	20 - 30											
64.8 or more	35 or more											
TOTAL		1	1	1	5	5	3	5	11	70	100	

Note. Symbol + indicates percentage value greater than 0 but less than 0.5 Values are to nearest whole percent. Not adjusted to make sums equal to total percentages.

Table 3.1 Annual Summary of Weather Observation at DCA  
(Percentage Frequencies of Ceiling-Visibility)

air carrier operations were recorded by the FAA-operated traffic control tower at DCA. Assuming an equal number of arrivals and departures, this amounts to 101,379 air carrier approaches to Washington. The previously cited summary of air traffic activity also reports that 12,323 air carrier instrument approaches were handled by the DCA approach control facility. Thus it can be concluded that 88% (89,056) of the approaches made during 1974 were visual approaches. The 4% difference in the two levels of visual operations is due in part to the fact that the meteorological observations were made on an hourly basis and, during any particular hour, conditions could improve to permit visual procedures and then revert to instrument conditions before the next observation is recorded. Since jet operations are limited to runways 18 and 36, an estimate of the number of visual approaches to runway 18 executed during 1974 can be gained from the statistics on observed wind direction. Over a one year period a wind out of the southern sector was observed 47% of the time [Reference 22]. Thus it can be deduced that approximately 40% (41,856 in 1974) of the approaches to DCA are made under visual conditions from the northwest along the course of the Potomac River. Likewise, it can be deduced that roughly 6% (5,792 in 1974) of the aircraft arriving at Washington National are denied clearance for the visual river approach. Sufficient data was not available to determine the relative utilization factors associated with the two instrument approaches to runway 18. However, statistics were available on the frequency of conditions when the visibility and ceiling were less than .9 Km (.5 nm) and 61 m (200 ft), i.e., below Category I. Thus statistics describing the number of operations affected by these adverse conditions represents a conservative estimate of aircraft denied approach to runway 18 since the lowest minimums for this runway are 1.9 Km (1 nm) and 219 m (720 ft). The climatological summary for Washington National Airport [Reference 24] indicates that, over a ten year period, the visibility and ceiling were

less than 0.9 Km (0.5 nm) and 61 m (200 ft) 0.55% of the time. Based on the 1974 traffic activity levels, the average number of aircraft delayed or diverted each year due to poor weather conditions would be greater than 260.

From the preceding discussion it is apparent that a curved instrument approach procedure with guidance provided by MLS would benefit operations at Washington National Airport in two respects. First, the capability of MLS to provide guidance along a curved path would enable the execution of the current visual approach procedure during instrument flight conditions and thus serve to reduce the overall noise impact. Also, MLS could provide the Category II guidance along the curved approach to runway 18 currently required to avoid the prohibited area to the north of the airport.

No quantitative measure was obtained describing the degree of improvement to be realized in acquiring this additional noise operational capability, since an extensive noise impact analysis of the Washington terminal area was considered outside the scope of this study. However, some relative figure of merit can be gained from a noise abatement case study of the New York Terminal Area (Reference 18]. This study involves the comparison of various aircraft on both ILS and curved noise abatement approaches to the LaGuardia and Kennedy air terminals. The basis for the comparison is derived from a simulation program which evaluates the total effect due to various noise related factors such as:

- The noise sensitivity of different surface areas, i.e., flight segments over water, cemeteries, or major highways are less likely to raise objections than segments over residential districts.
- The noise generating characteristics of various aircraft measured in terms of the minimum distance at which a specific noise level is perceived.

- The relative density of population centers described in terms of a weighting factor ascribed to a geographically-located cell.

The program is exercised for various scenarios involving different airports, runway orientations, approach paths, and aircraft mixes to yield three measures of the noise impact:

- The Situation Index, measured in acre-minutes, to reflect the exposure time for noise-sensitive surface areas for a specific scenario.
- The Revised Situation Index, also measured in acre-minutes, to reflect the exposure time for population cells for a specific scenario.
- The Population Exposure Index, measured in people-minutes, to reflect the number of people exposed and the exposure time for a specific scenario.

The Population Exposure Index was used as the basis for comparing ILS and MLS-guided curved approaches since this is the most meaningful measure of the annoyance due to aircraft noise. The most dramatic comparison resulting from this analysis involves the ILS approach and the MLS noise abatement approach to runway 13R at JFK International. The MLS noise abatement approach is roughly equivalent to the Canarsie approach described earlier. When compared to the ILS approach to 13L (there is no ILS approach to 13R), the MLS noise abatement approach results in an 85% reduction in the Population Exposure Index. A similar comparison for 13L indicates a 72% reduction. Taken alone, these impressive numbers might be somewhat misleading as to the relative merits of MLS curved approaches as a means to reduce the impact of noise. The comparative evaluation is conditioned on the fact that the runway considered is in active use and the weather dictates that an instrument approach is required. However, given that the visibility and ceiling at JFK are greater than 5.6 Km (3 nm) and 305 m (1000 ft) 87% of the year [Reference 25] and that, during these periods, the Canarsie approach to 13L or 13R is preferred,

the exposure index must be adjusted to account for the reduction in the overall noise effect incurred in the operation of a given runway. To gain an even broader indication of the impact of MLS noise abatement procedures, consideration should also be given to the entire schedule of operations at JFK. A rough estimate of this total effect was made and is summarized in Table 3.2. The column headings are described as follows:

- Use - A factor proportional to the runway utilization.
- Noise Exposure - A factor related to the population exposure index reported in Reference 18 with the index for runway 13R used as a basis.
- Relative Impact - The product of the use, exposure and condition factors. The condition factor is indicative of the average occurrence of weather conditions dictating visual (8.7) or instrument (1.3) procedures.
- Total Impact - For MLS implementation, the sum of the MLS and Visual Relative Impacts. The total impact for ILS is similarly computed.

The ILS and MLS noise exposure factors for runways 13L and 13R were based on the information provided in Reference 18. The remaining factors are estimates based on the following assumptions:

- Visual and MLS noise abatement approaches are identical; therefore, the noise exposure factors for each are identical.
- The noise exposure incurred on approach to runway 4 over Long Island Sound is roughly equivalent to that for the Canarsie visual approach to runway 13R.

RWY	USE	NOISE EXPOSURE		RELATIVE IMPACT			TOTAL IMPACT	
		Visual/MLS	ILS	Visual	MLS	ILS	MLS	ILS
4R	1.1	1	1	9.6	1.4	1.4	11.0	11.0
13L	2.8	1.8	6.5	43.8	6.6	23.7	50.4	78.5
13R	1.3	1	6.5	11.3	1.7	10.9	13.0	22.2
22L	2.8	6.5	6.5	158.3	23.6	23.6	181.9	181.9
22R	.2	6.5	6.5	11.3	1.7	1.7	13.0	13.0
31L	.5	1.4	1.4	6.1	.9	.9	7.0	7.0
31R	1.3	1.4	1.4	15.8	2.4	2.4	<u>18.2</u>	<u>18.2</u>
TOTAL							<u>294.5</u>	<u>331.8</u>
%							11.2%	

Table 3.2 Total Impact of MLS Noise Abatement Approaches at JFK

- The population densities for the areas northeast and northwest of the airport are nearly identical; therefore, the exposure indices for ILS approaches to 13L, 13R, 22L, and 22R are assumed equal.
- No significant advantage could be gained from an MLS noise abatement approach to 22L or 22R .
- The populated area exposed to noise from aircraft approaching on 31L or 31R was judged to be greater than that for 13R (visual) but less than that for 13L (visual).

The resulting performance measures were not evaluated with the intention of demonstrating the absolute merits of curved approaches for noise abatement. Rather, the intent of the exercise was to demonstrate that a comparison of the noise figures resulting from an ILS approach and MLS approach approximating a visual noise abatement procedure is not in itself a realistic indication of the benefits of MLS guidance. When considered in relation to all approach conditions, the dramatic noise reductions demonstrated for a specific profile appear less significant. Translating these observations to the Washington National case, it is doubtful that a 10% overall improvement in the noise environment could be realized with the application of MLS guidance to the visual approach procedure since less than 20% of the current approaches are conducted under instrument flight conditions.

As indicated earlier, no Category II guidance capability is provided on approach to runway 18. The prohibited area enclosing the White House and the Capital is situated less than 3.7 Km (2 nm) to the north of the threshold and in the direct path of the extended runway centerline. The width of this zone is such that at least a 20° turn is required to align the final approach path with the runway centerline without violating the restricted area.

Thus a straight-in approach utilizing the narrow beam ILS guidance is impossible. With the current complement of navigation aids, the minimum visibility and ceiling requirements [1.9 Km (1 nm) and 219 m (720 ft)] are achieved with the VOR/DME approach. Thus the broader coverage afforded by MLS would enable guidance along the required curved approach path and thus serve to increase the landing capability on runway 18. To gain some relative measure of the operational advantage provided by MLS guidance on approach to runway 18, consider the estimated costs incurred by the airlines due to delays, diversions, and cancellations whenever Category II conditions prevail and when the wind direction dictates the use of this runway. This amount would then represent the dollar benefit of implementing MLS to achieve curved approaches. Based on previously reported traffic activity and weather observations, it can be estimated that there are 48,000 approaches to runway 18 each year. The data reported in the Climatological Summary for DCA [Reference 24], indicates that Category II conditions occurred for a period less than 90 minutes at Washington National 0.23% of the time and that the average duration for each occurrence was 26.4 minutes. If it is assumed that each of these occurrences resulted in an enroute delay, then approximately 49 hours of delay time were incurred by the airlines in waiting for the weather to improve and thus permit a landing on runway 18. (Recall that this figure does not include delays due to Category III conditions since it was assumed that MLS would provide only Category II landing capability). Assuming a \$600 per hour delay cost, [Reference 26], the resulting delay penalty amounts to \$29K per year. Further, if the adverse weather prevailed for a period greater than 90 min, then it is probable that an approaching aircraft was diverted to another airport or the flight was cancelled. In the Climatological Summary, 22 of these occasions (Category II only) were reported

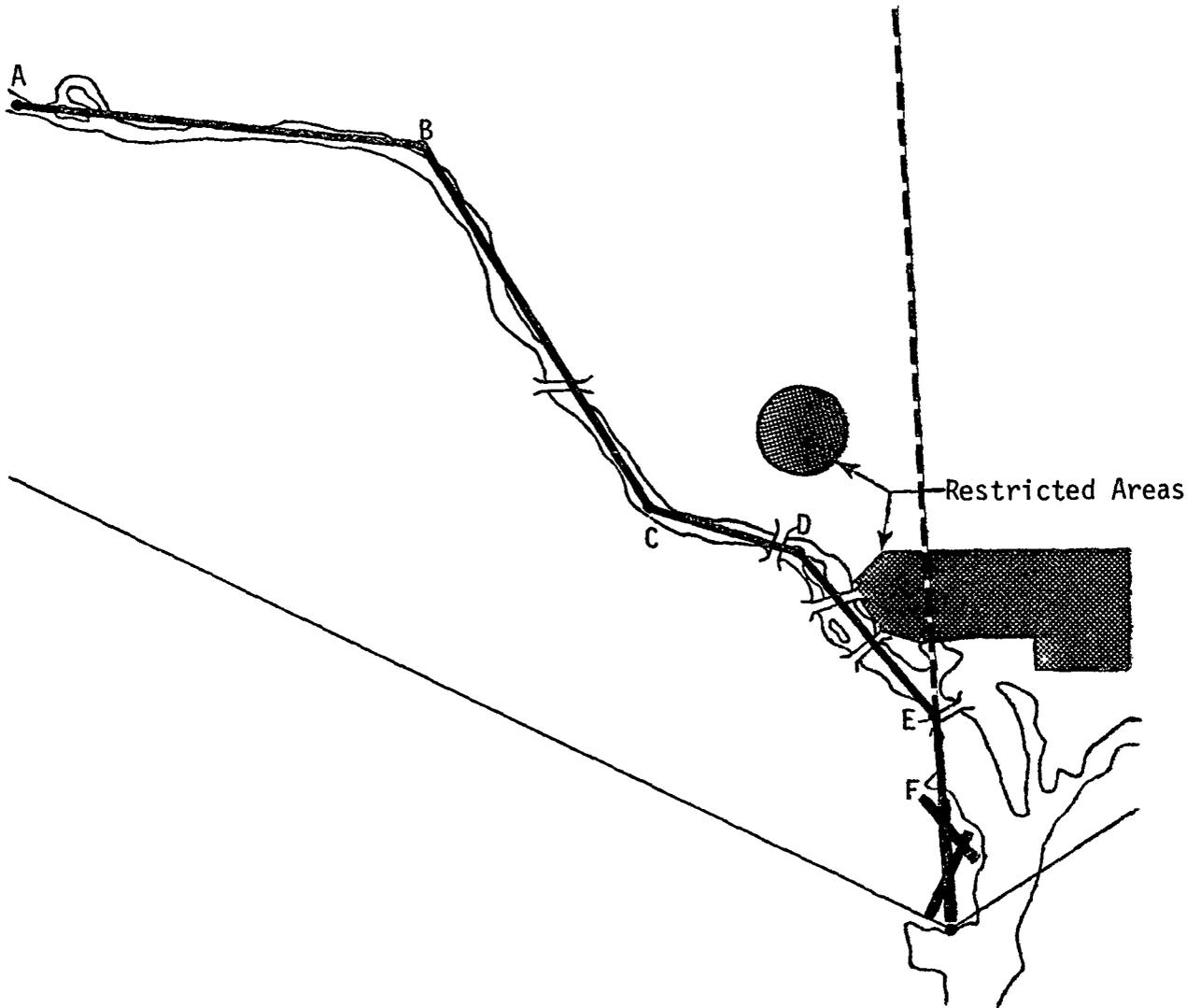
over a ten year period and the average duration of each occurrence was 140.6 minutes. Based on this information, it was estimated that approximately 28 aircraft destined to land on runway 18 were either diverted or cancelled due to inclement weather. At an estimated \$1500 per diversion or cancellation, [Reference 26], the consequent penalty results in a loss of \$42K per year. Thus, if MLS were installed on runway 18 at DCA to enable curved approaches under Category II conditions, the annual savings to the airlines due to the increased operational capability would amount to \$71K. It should be recognized that this amount is probably a conservative estimate, since the current approach guidance facilities for runway 18 do not even permit operations to the minimum extent of those conditions defining the lower bounds of Category I.

Having identified the possible applications and potential for curved approaches, the study then focused on the definition of the curved flight path and the consideration of the requirements to implement these approaches. Throughout the study, the basis for examination was the approach to runway 18 at the Washington National Airport. The factors considered include:

- Path Definition
- Avionics Requirements
- Pilot Sensitivities

Each of these factors will be discussed briefly in the following paragraphs.

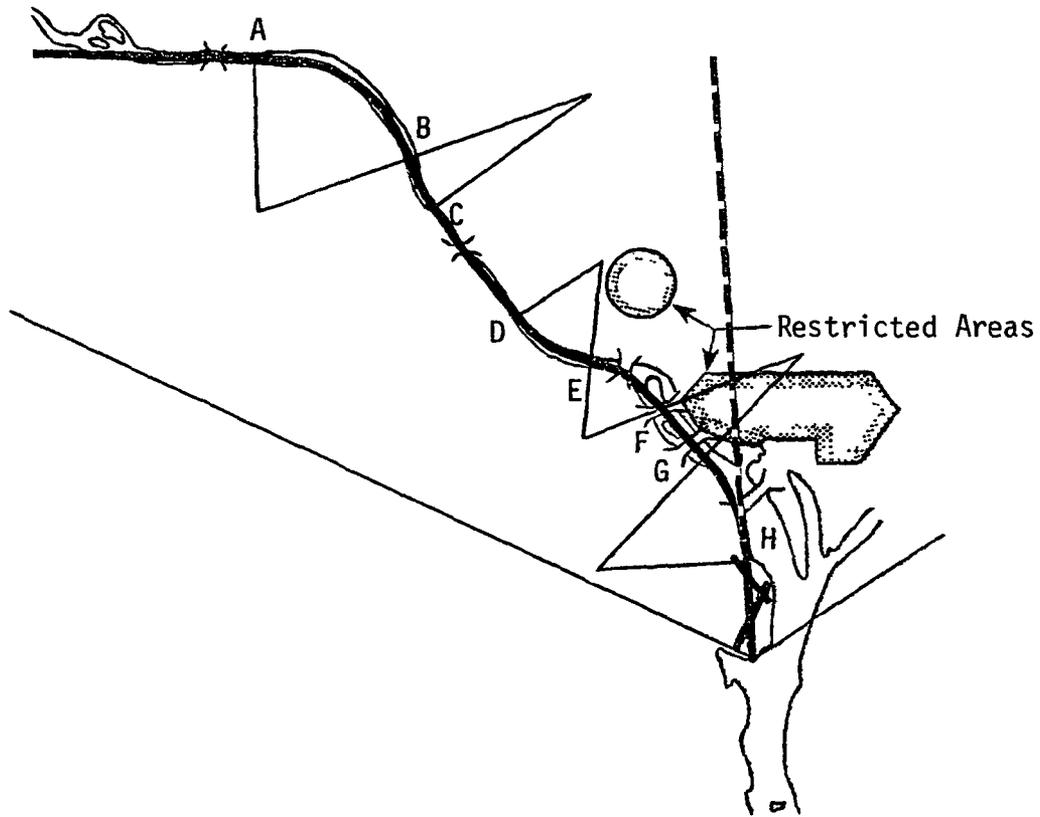
The consideration of "curved" approaches to Washington National Airport is not a concern unique to this study. In a recent report [Reference 21], three alternative curved paths involving sequences of line segments in both the horizontal and vertical planes were proposed as noise abatement procedures utilizing MLS. One of these approaches is described by five segments and is a reasonable straight-line approximation to the course of the Potomac (Figure 3.5). Segment lengths range from 1.6 Km (.85 nm) to 8.0 Km (4.34 nm), while the turns required to execute the segment-to segment transitions range from approximately 35 degrees to



<u>Segment</u>	<u>Length, Km(nm)</u>	<u>Time, Sec., at 62 m/s (120 kt)</u>
A-B	6.85 (3.70)	111.0
B-C	8.06 (4.35)	130.5
C-D	2.59 (1.40)	42.0
D-E	3.89 (2.10)	63.0
E-F	1.57 (0.85)	25.5

Figure 3.5 Linear Segment Approach to DCA - Runway 18

55 degrees. To execute these leg-to-leg transitions without deviating significantly from the intended path requires that the autopilot include an automatic turn anticipation capability. Since the transition guidance mode involves a nominal bank angle or, equivalently, a nominal heading rate command, would it not be possible without major modifications to the guidance system to utilize this functional capability to execute a curved approach consisting of arc as well as line segments? If this could be accomplished, then a path more closely aligned with the river corridor could be specified. In answer to the previously posed question, slight modification of current avionics would enable guidance along an arc segment. In fact, the functional design of the Boeing-developed Advanced Guidance and Control System (AGCS) onboard the NASA/TCV includes the capability for guidance during the turn to intercept the following track. Thus it was considered appropriate to design an arc-segment approach approximating the nominal flight path of the visual noise abatement procedure. The exercise resulted in the approach path displayed in Figure 3.6. The path involves six arc segments and one straight-line segment. Each arc segment is described by two points, an initial waypoint and a point indicating the center of curvature. The straight-line segment is described by a single waypoint. Thus, in three dimensions, the curved approach path approximating the visual approach requires the specification of 42 parameters (range, azimuth and elevation for each intermediate point and the final point). The five segment approach previously mentioned involves 18 parameters. Undoubtedly, the additional complexity involved in the description of the arc-segment approach might raise objections with regard to both the additional waypoint storage and communication requirements. However, if the current trend in the design and production of memory storage elements continues, then it is doubtful that future technology would hinder



<u>Segment</u>	<u>Radius, Km(nm)</u>	<u>Length, Km(nm)</u>	<u>Time, Sec, at 62 m/s(120 Kt)</u>
A-B	3.61 (1.95)	3.87 (2.09)	62.74
B-C	4.20 (2.27)	1.37 (0.74)	22.06
C-D	2.28 (1.23)	3.19 (1.72)	51.68
D-E	1.93 (1.04)	1.65 (0.98)	29.42
E-F	1.93 (1.04)	1.91 (1.03)	30.83
F-G	3.63 (1.96)	1.52 (0.82)	24.72
G-H	3.50 (1.89)	2.59 (1.40)	41.85

Figure 3.6 Arc Segment Approach to DCA - Runway 18

the implementation of guidance and control components capable of storing the number of parameters required to define a complex approach path. Further, it is not impossible to imagine that, at some future time, approach paths will either be pre-stored or communicated to the aircraft system via a digital data link.

Another consideration was the design of an autopilot to enable guidance along a continuously changing path. Typically, an autopilot derives a control signal, either a heading rate or a bank angle command, based on the heading error and the lateral deviation of the aircraft from the desired track. To modify the design to achieve guidance along a curved path, several considerations are evident. The cross-track deviation must be computed relative to the arc and the desired heading varies continuously with respect to the turn angle accomplished. To execute the turn properly a control signal proportional to the radius of curvature and the nominal groundspeed must be included in the control law to achieve the necessary bank angle. If the groundspeed is assumed constant over a given segment, then the bank angle command could be regarded as a nominal heading command, and, in this sense, the resultant effect could be interpreted as a bias term causing the controller to lead the desired heading and "catch-up" to the continuously changing heading. The subject of guidance system design changes to accommodate curved paths is of principal concern in following sections and thus will be addressed in more detail in later discussions.

The third consideration was the pilot's sensitivity to non-stabilized approaches in the manual flight mode. Although curved approaches look very good on paper, it will be some time before the procedure is ever committed to daily practice. The pilot's reaction was clearly expressed by John Baker, special assistant to the president of the Air Line Pilots Association in the

April, 1976, issue of The Aviation Consumer. Mr. Baker was quoted as saying that "Until it has been demonstrated that curving approaches can be flown safely, we're just going to refuse to do them". Mr. Baker's comment is a general reflection of the pilot preference for a stabilized instrument approach from the outer marker to the runway threshold. Along the stabilized approach the aircraft is aligned with the localizer beacon and set up on the proper glideslope. This relatively simple flight path minimizes the demands on the pilot's attention to the instruments. If the current display philosophy were employed to guide the pilot in maintaining a curved path, then constant attention would be required to track the continuously changing flight path, since the cockpit instrumentation in common use reflects only the instantaneous state of the aircraft. Under visual conditions the reaction to curved approach paths is understandably different. As indicated earlier, visual curved approach procedures are in common use to achieve low noise approaches and to avoid obstacles in the vicinity of the airport. The obvious difference in the reactions to curved paths is that, under visual conditions, the features indicating the projected ground track enable the pilot to establish his maneuver strategy in advance while, under instrument conditions, he must respond to an immediate indication of the deviation from the nominal profile without reference to the intended flight path in advance of the aircraft. The obvious key word in this discussion is anticipation. If the display indicating guidance information would enable the pilot to anticipate the control actions required to maintain the desired flight path, then his attitude toward curved approaches might be softened.

## 3.2 ENERGY MANAGEMENT OPERATIONAL CONSIDERATIONS

Many constraints are imposed upon aircraft operating in the National Airspace System. Some of these limitations are due to the characteristics and limitations of the aircraft and its engines while others are imposed by the air traffic control system in which the aircraft is operated. The operational restrictions are imposed upon the aircraft to provide assurance that the aircraft is operated in a safe manner both individually and collectively with respect to the other aircraft that share nearby airspace. Constraints are imposed upon the aircraft through other less formal but equally important considerations. Aircraft economics and passenger comfort limits fall into this category. Obviously, if an aircraft is operated in an uneconomical manner the aircraft operator will not be interested in retaining the flight procedures which cost him money. On the other hand, if the flight procedures cause the passengers to be uncomfortable during any stage of the flight, revenues can be lost because passengers may divert to another airline or to another mode of transportation. The following paragraphs describe, in some detail, the constraints that are imposed upon civil aircraft in the U.S. at the present time.

### 3.2.1 Airframe and Powerplant Constraints

The motion of the aircraft is entirely governed by the thrust, drag and lift characteristics of the engines and the airframe respectively, and the control inputs provided by the pilot and the autopilot system. The lift and drag characteristics of the aircraft are determined by the configuration of the various components of the aircraft structure such as the wing, fuselage, the control surfaces, and auxiliary lift and drag components such as the flaps. The lift and the drag forces acting upon the aircraft are a function of speed, altitude and weight. A corresponding change in the thrust level and the fuel flow of the engines can be observed as the aircraft changes altitude or airspeed.

The flight controls that govern the vertical profile of the aircraft are primarily the throttle, and the elevators. The throttle, of course, adjusts the amount of thrust acting upon the aircraft, while the elevator deflection changes the forces and moments acting upon the airframe to cause the aircraft to climb or descend.

The performance profile will be constrained by the maximum and minimum thrust available from the engines as well. For given altitudes and speeds there is a limit to the climb or descent rate that can be achieved through changes in the throttle setting.

The throttle controls are often set at maximum continuous thrust during climbout and at flight idle during descent. The elevator trim is then adjusted to achieve a predetermined airspeed, Mach number, rate of climb or angle of attack. Consequently, the observable performance parameters are different from the controls in these instances. Engine set points can be computed based on predicted performance capabilities of the engines and the state of the aircraft in terms of weight, speed and altitude and environmental effects such as temperature. These set points are used to relieve the pilot of some workload during the flight so that the pilot does not have to "hunt" for the proper throttle setting. The procedure for adjusting set points makes use of precomputed tables or graphs. A typical data sheet indicating desired throttle settings for takeoff is shown in Figure 3.7. However, these graphic aids are not well suited to set point adjustments on a continuous basis but rather intended to serve as a guide to direct changes at specific points in the flight such as the beginning of cruise, holding at a specified speed and altitude and during climb, descent and approach.

# TAKEOFF

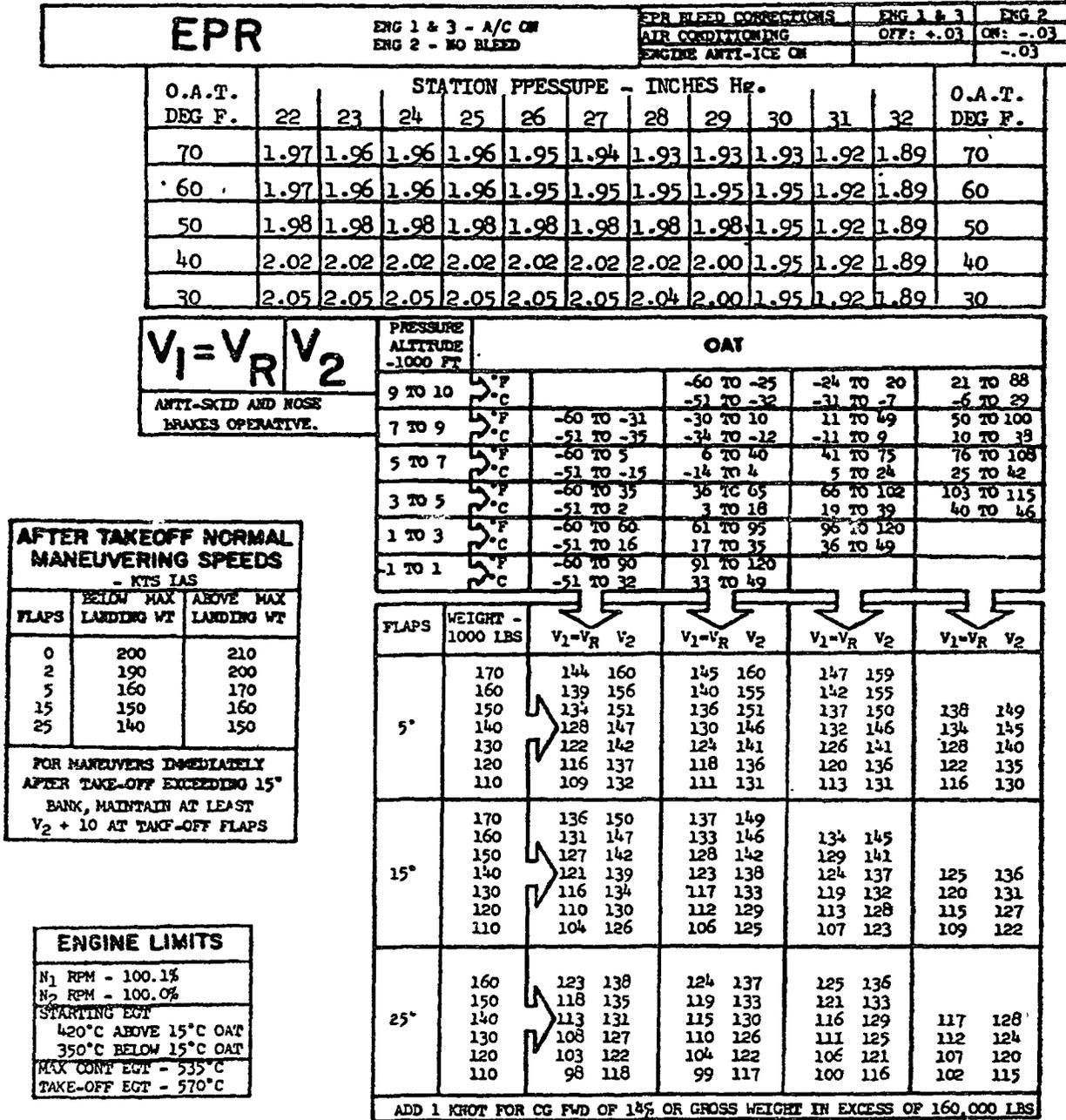


Figure 3.7 Typical Takeoff Data Table

### 3.2.2 Economic Constraints

The operation of a turbojet aircraft costs a considerable amount of money both in terms of cost per flight hour and cost per pound of fuel. Consider, as an example, a 370 Km (200 nm) stage length for a B737-200. The aircraft consumes 2040 Kg (4500 lbs) of fuel costing \$340 [16.5¢/Kg (7.5¢/lb)]. The costs involved in the airside operations for this 45 minute flight would be equivalent to the fuel expense of \$340, since the cost per hour of operation for the B737-200 was estimated to be \$450. Thus, the most energy efficient method of flying an aircraft may well be more costly than a faster, less fuel efficient method of flight control because a longer flight time is required. Consequently, both time and fuel are important in achieving an efficient energy management flight procedure. Crew costs, aircraft maintenance and overhaul, and, to some extent, insurance rates are all based upon the number of hours flown. Other costs such as depreciation may be stated in a cost per flight hour manner but are less sensitive to incremental flight time than all those mentioned previously.

When examining time and fuel costs it is important to consider the block-to-block costs for a specified flight. That is, the time and fuel expenditures for the entire trip are of more interest than are the expenditures during the various segments of flight such as climb, cruise, descent, holding and approach. Consequently, when costs for different phases of flight are compared for two different procedures, it is important that the aircraft is started and terminated at the same initial and final conditions in terms of speed, altitude, and distance. If such is not the case, the basis for comparison is invalid. All of the comparisons made in this report on the benefit of various profile management techniques will be on a compatible initial and final state basis.

### 3.2.3 Air Traffic Control Constraints

In the U.S. at the present time, the air traffic control system has a profound influence upon the operational procedures of air carrier types of aircraft.

Air traffic control is primarily concerned with keeping a safe and efficient flow of traffic between the airports. The constraints that this control places upon aircraft may be divided into two categories, terminal area and enroute.

In the terminal area aircraft are generally arriving to or departing from an airport. In busy areas aircraft must be kept sufficiently separated so that they can operate safely into and out of the airport. In many instances speed controls are requested by the controller so that the aircraft can be suitably separated. In busier situations some aircraft must be circled in holding airspace areas in order that the controller can sequence traffic into the runway. Below 3048 m (10,000 ft), aircraft are restricted to speeds less than 129 m/s (250 knots) indicated airspeed in the U.S. [Reference 27] so that the see-and-avoid concept of traffic control may be effectively used in the congested airspace at those low altitudes in visual meteorological conditions. These low speeds impose a definite constraint upon jet aircraft as they (the aircraft) are usually designed for optimum efficiency at somewhat higher speed operations. Other ATC-related operational considerations which may affect the aircraft in the terminal area include altitude assignments and noise abatement procedures. Crossing arrival and departure routes often produce requirements for aircraft to hold at a lower than desired altitude until some altitude control point is reached. This altitude control point may be defined by some navigation fix such as a VOR facility, a VOR intersection or a radar fix defined by the controller. The holding of the aircraft at a less than desired altitude often imposes both fuel and time penalties on the aircraft operations.

In enroute airspace the constraints upon the aircraft are generally less restrictive but they apply for a longer period of time. In some instances these controls are often similar to those required in the terminal area. Both speed controls and altitude controls are used for traffic separation at jet cruise

altitudes. In particular, altitude controls are in effect at all times. From FL180 (18,000 ft) to FL290 altitudes are assigned by ATC in 305 m (1000 ft) increments while above FL290 610 m (2000 ft) altitude increments apply to reflect the lower altimeter sensitivities at these altitudes. In addition eastbound traffic flies at odd thousands of feet and westbound traffic flies at even thousands of feet up to FL280. Above this altitude east bound traffic flies at FLs 290, 330, 370, etc., and westbound traffic flies at FLs 310, 350, 390, etc., unless otherwise modified by ATC. This implies that above FL290 aircraft may have to fly up to 1220 m (4000 ft) below desired cruise altitude to satisfy ATC requests. One additional operational consideration which can cause the aircraft to operate at non-optimum altitudes is the identification of the desired start-descent point in the presence of unknown wind and temperature variations. If there is an unforecast headwind, the aircraft will descend in a steeper gradient than with no wind and an aircraft descending with tailwind will have a shallower gradient. The headwind aircraft will reach his desired altitude before reaching the desired ground position and will consequently have to cruise at the lower, slower and less efficient altitude. The tailwind aircraft will reach his ground position before reaching his desired altitude and will be higher and faster than desired and will usually require additional drag to be added, again resulting in less efficient operation of the aircraft. Consequently, identification of the optimum start-descent point can provide more economical aircraft operation.

#### 3.2.4 Passenger Comfort Limits

The passenger comfort limits which affect the vertical profile are the vertical acceleration and the flight deck angle. Acceleration limits are usually placed at .15g or less which precludes the use of sudden changes in the elevator deflection to produce rapid changes in the flight path angle.

The flight deck angle is limited to 15° in accordance with normal airline ATA operating procedures on most civil airline flights. This deck angle would definitely be a constraint on smaller lightly loaded aircraft but not a limitation on long haul heavier aircraft. Recently Northwest Airlines has started to deviate from this policy slightly in order to achieve reduced noise climb-outs and more fuel efficient profiles [Reference 28].

### 3.3 SUMMARY OF SECTION 3

The most significant conclusion resulting from the operational consideration of a curved approach to Washington National was the observation that this terminal would realize substantial benefits from the installation of an MLS facility. The principal factor contributing to this advantage is the unique geographic situation of the Washington airport. The security sensitive areas in line with the only runway certified for commercial operations dictate that approaches to runway 18 involve a turn to intercept the final approach path in the immediate vicinity of the threshold. Since the landing aids in current use were not intended to serve this function, the pilot must rely on visual cues to execute this turn. Thus the prescribed minimums for the approach to this runway are well above those established for an ILS approach. With MLS providing continuous guidance during the turn to final, the existing minimums could be reduced considerably resulting in an increase in the airport utilization factor and a decrease in expenses to the airlines to accommodate delays and diversions.

The constraints imposed by the aircraft systems, the economic considerations, the air traffic control system, and the regard for passenger comforts were reviewed with respect to the energy management issue. Perhaps the greatest current restriction relating to the aircraft management system are the procedures employed by the flight crew in adjusting engine throttle settings to accommodate the variations in the aircraft parameters and the environmental conditions. These

current procedures are not readily adaptable to the situation where continuous changes in the throttle settings are required to maintain a fuel-optimum profile. The economic tradeoffs involved in the energy management issue are also significant. Although the minimum fuel climb or descent may be cost effective from the standpoint of fuel economy, it may not be efficient with respect to the factors influenced by the total flight time between the point of origin to the point of destination. Further, consideration must be given to the constraints imposed by the ATC system to maintain a safe and orderly flow of traffic within the terminal area. Complex traffic patterns in the vicinity of the terminal area may hinder the achievement of fuel optimum flight profiles. The holding of aircraft at specified altitudes at crossing arrival and departure routes imposes both time and fuel penalties on aircraft operations. The consideration of passenger reactions to unusual vertical accelerations and deck angles is a significant but not dominant factor. Greater tolerance levels might be achieved if the passengers are advised of the abnormal situation in advance of the maneuver.

## 4.1 AIRCRAFT GUIDANCE SYSTEM MODELING

One of the principal objectives of the visual approach to runway 18 at Washington National is to minimize the noise impact by confining the ground track of approaching aircraft to the corridor defined by the Potomac River. Thus, if the procedure is to be accomplished under instrument flight conditions, the course deviations due to the response characteristics of the guidance system and the measurement errors inherent in the navigation sensors must not exceed the limits defined by the width of the river. To achieve this objective, the guidance accuracy along the approach should be on the order of 185 m ( $\pm 0.1$  nm). To examine the feasibility of achieving this degree of precision, a simulation was developed to approximate the lateral response of an aircraft along a curved approach path. The simulation involved the modeling of the functional elements relating to:

- The guidance control law and the dynamics of the autopilot and aircraft systems
- The specification of the parameters defining the curved path and the logic to sense the completion of one segment
- The evaluation of the cross track deviation between the current aircraft position and the intended nominal position
- The effect of measurement errors
- The impact of environment disturbances

4.1.1 Aircraft Guidance Simulation

The simulation is described by the schematic representation shown in Figure 4.1. The parameters shown are described by:

$\phi$  = aircraft bank angle

$\phi_0$  = nominal bank angle required to execute turn

$\phi_C$  = bank angle command to autopilot

$\phi_{\max}$  = limiting value of bank angle

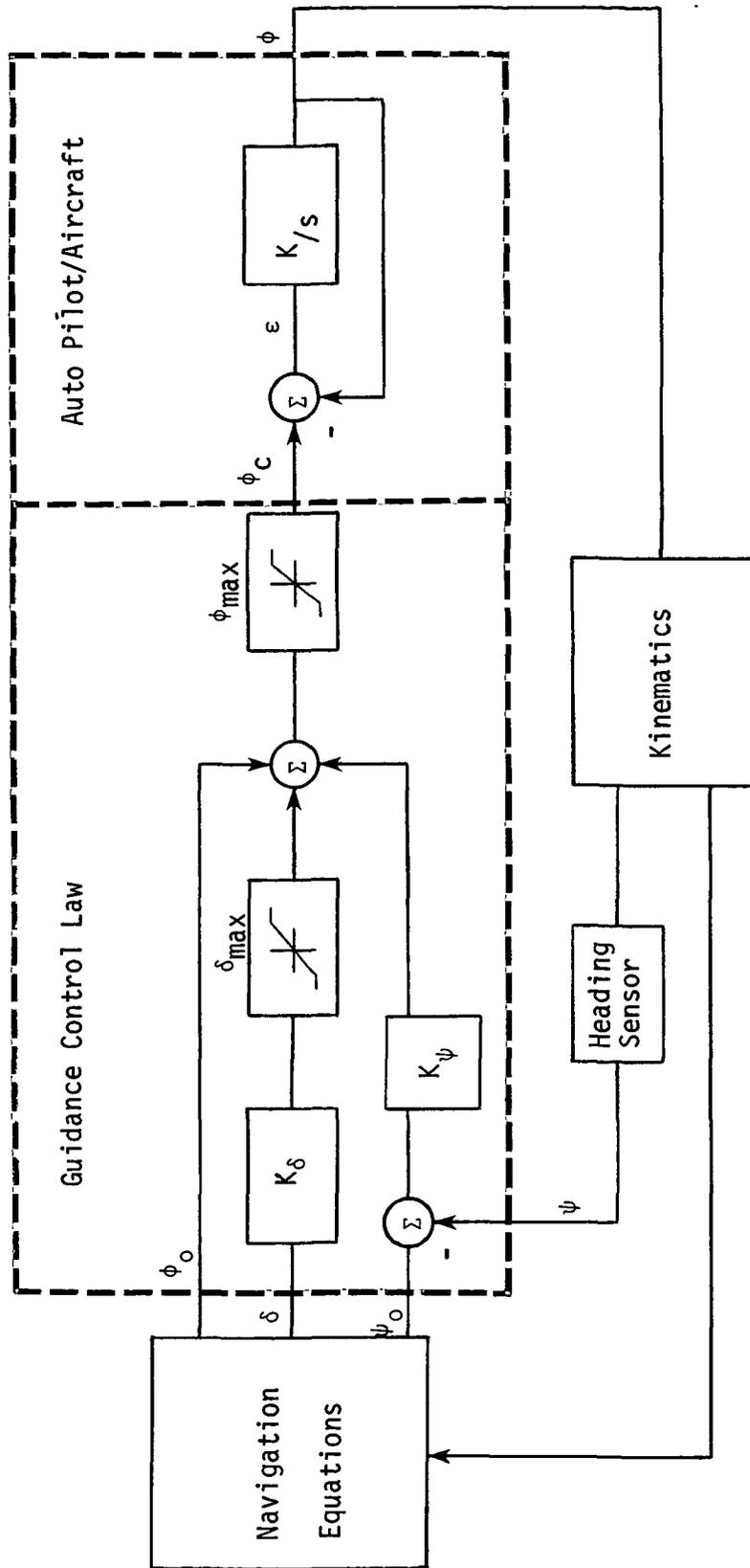


Figure 4.1 Aircraft Guidance System Model

- $\psi$  = aircraft heading
- $\psi_0$  = nominal track heading
- $\delta$  = cross track deviation
- $\delta_{\max}$  = maximum cross track deviation
- $\epsilon$  = error signal analogous to the deflection of the aircraft control surfaces

The functional elements depicted in this block diagram are described in detail in the following paragraphs.

The lateral aircraft dynamics and autopilot characteristics were combined on the assumption that the dominant factor in the design of the control system was the consideration of passenger reaction to roll maneuvers [Reference 29]. Thus the transient response of the aircraft to a deflection of the control surfaces was ignored and a gain factor was assumed to represent the aircraft dynamics. The roll rate developed in response to a control command is then integrated to derive the aircraft bank angle. The gain parameter was determined by practical considerations. Referring to Figure 4.1., the roll-axis response is determined by:

$$\dot{\phi} = K(\phi_c - \phi)$$

The maximum roll rate is achieved when the bank angle is initially zero and the bank angle limiter is saturated, i.e.,  $\phi_c = \phi_{\max}$ . Thus,

$$K = \frac{\dot{\phi}_{\max}}{\phi_{\max}}$$

With  $\dot{\phi}_{\max} = 10$  deg./sec.,  $\phi_{\max} = 30$  deg.,  $K = 0.33$ . The limit on the cross track deviation,  $\delta$ , was included to prevent an orbiting problem. If the limit were not applied and the deviation from the intended track was significant enough to dominate all other items in the control law and possibly saturate the bank angle limiter, then the aircraft would be driven to turn constantly without intercepting the desired track. If the cross track deviation exceeds the specified

limit without saturating the bank angle limiter, then control is effected by the following differential equation:

$$\dot{\phi} = K(\phi_0 - \phi) + K[K_{\psi}(\psi_0 - \psi) + K_{\delta} \delta_{\max}] \quad (4.1)$$

Recognizing that  $(\psi_0 - \psi)$  is proportional to the integral of  $(\phi - \phi_0)$ , one is led to conclude that the equilibrium solution to the differential equation is determined by

$$\begin{aligned} \dot{\phi} &= 0 \\ \phi &= \phi_0 \\ (\psi - \psi_0) &= \frac{K_{\delta} \delta_{\max}}{K_{\psi}} = \alpha \end{aligned} \quad (4.2)$$

The latter equation implies the controller directs that the aircraft intercept the desired heading at a fixed angle,  $\alpha$ . Thus  $\alpha$  is one of the control law design parameters and a value of 30 degrees was assumed in the simulation. Differentiating (4.1) and recalling that  $\dot{\psi} = g \phi / v$  ( $v$  = groundspeed), yields the following equation:

$$\ddot{\phi} + K\phi + \frac{(KK_{\psi}g)\phi}{v} = \frac{(K_{\psi}g)\phi_0}{v}$$

For a critically damped response to a step change in the nominal bank angle command, the following relationship must apply

$$\frac{(KK_{\psi}g)}{v} = \frac{K^2}{4}, \text{ or} \quad (4.3)$$

$$K_{\psi} = \frac{(K)}{4g} v.$$

As the aircraft approaches the desired track and the cross track deviation drops below the saturation threshold, the combined controller and aircraft response is governed by

$$\dot{\phi} = K(\phi_0 - \phi) + K[K_{\psi}(\psi_0 - \psi) + K_{\delta} \delta]. \quad (4.4)$$

As aircraft heading nears the nominal heading the following approximation applies

$$\dot{\delta} = -V \sin(\psi_0 - \psi) \approx -V(\psi_0 - \psi). \quad (4.5)$$

Differentiating (4.4) twice and substituting (4.3) and (4.5) yields the differential equation:

$$\ddot{\phi} + K \dot{\phi} + \frac{K^2}{2} \phi + KK_{\delta}g\phi = KK_{\delta}g\phi_0.$$

whose characteristic equation is

$$s^3 + Ks^2 + \left(\frac{K}{2}\right)^2 s + KK_{\delta}g = 0 \quad (4.6)$$

The specification of the gain parameter  $K_{\delta}$  was based on a root locus analysis of the open loop transfer function

$$\frac{KK_{\delta}g}{s(s+K/2)^2}.$$

For a critically damped system with minimum rise time,

$$K_{\delta} = \frac{K^2}{54g}$$

such that the roots of (4.6) are at

$$\delta = -K/6 \text{ (double root)}$$

$$\delta = -2K/3.$$

Having determined  $K_{\delta}$ , it is possible to evaluate  $\delta_{\max}$  from (4.2), i.e.,

$$\delta_{\max} = \frac{27V}{2K}.$$

The parameter specifications indicated above are repeated in Table 4.1 together with the values assumed for the simulation. In those cases where the parameters are velocity dependent, a ground speed of 62 m/s (120 kt) was assumed.

#### 4.1.2 Path Definition

As indicated earlier, the arc segments of the curved path are specified by two parameters, the initial point of the segment and a point indicating the center of curvature for the arc. The straight-line segments are specified by a single parameter, the initial point of the segment. The navigation equations involving the computation of cross track deviation and the desired heading were formulated on the basis of a computational reference frame dependent on the type of segment

Parameter	Significance	Units	Algebraic Relationship	Simulation Value
$\phi_{max}$	Max Bank Angle	deg		30.0
$\dot{\phi}_{max}$	Max Roll Rate	deg/sec		10.0
$\alpha$	Track Intercept Angle	deg		30.0
$g$	Gravitational Constant	m(ft)/s <sup>2</sup>		9.81(32.2)
$V$	Groundspeed	m(ft)/s		61.7(202.5)
$K$	Autopilot Gain	s <sup>-1</sup>		.33
$K_{\psi}$	Heading Error Gain	N.D.	$KV/4g$	.52
$K_{\delta}$	Cross Track Deviation Gain	deg/m(ft)	$57.3K^2/54g$	$1.2(3.6) \times 10^{-4}$
$\delta$	Max Cross Track Deviation	m(ft)	$K_{\psi}\alpha/K_{\delta}$	1321(4333)

Table 4.1 \_ Control Law Parameters

flown and the location of the initial waypoint. For the straight-line segment, the reference frame is centered at the initial waypoint with the vertical z- axis in the direction of increasing altitude, i.e., up. Relative to the runway-centered coordinate system the y-axis is the normalized projection of the path segment vector  $(w_2-w_1)$  on the plane normal to z, (Figure 4.2), i.e.,

$$y_1 = v/|v|$$

where

$$v = (w_2 - w_1) - [(w_2 - w_1) \cdot z_1] z_1 .$$

The x-axis completes the right-handed coordinate system, i.e.,

$$x_1 = y_1 \times z_1 .$$

The transformation from the computational to the runway-centered reference frame is accomplished by

$$p_0 = Tp_1 + w_1$$

where the columns of the matrix T are the unit vectors  $x_1, y_1, z_1$ . The command heading and nominal bank angle are both zero while the cross track deviation is

computed as the projection of the aircraft position relative to computational reference frame on the x-axis

$$\delta = p_1 \cdot x_1 .$$

The flight segment is concluded when

$$p_1 \cdot x_2 = |w_2 - w_1| .$$

For the arc segment, the computational frame is located at the center of curvature with the z-axis up, as before, and the x-axis directed towards the initial waypoint, i.e.,

$$x_2 = v / |v|$$

where

$$v = (w_2 - c_2) - [(w_2 - c_2) \cdot z_2] z_2 .$$

The transformation from the track-oriented to the runway-centered coordinates is completed by

$$p_o = Sp_2 + c_2$$

where the columns of the transformation matrix are the unit vectors  $x_2, y_2, z_2$ . For the arc segment, the command heading,  $\psi_o$ , varies continuously with respect to the aircraft's progress along the arc and the nominal bank angle,  $\phi_o$ , is proportional to square of the groundspeed,  $V$ . These two control parameters are determined by

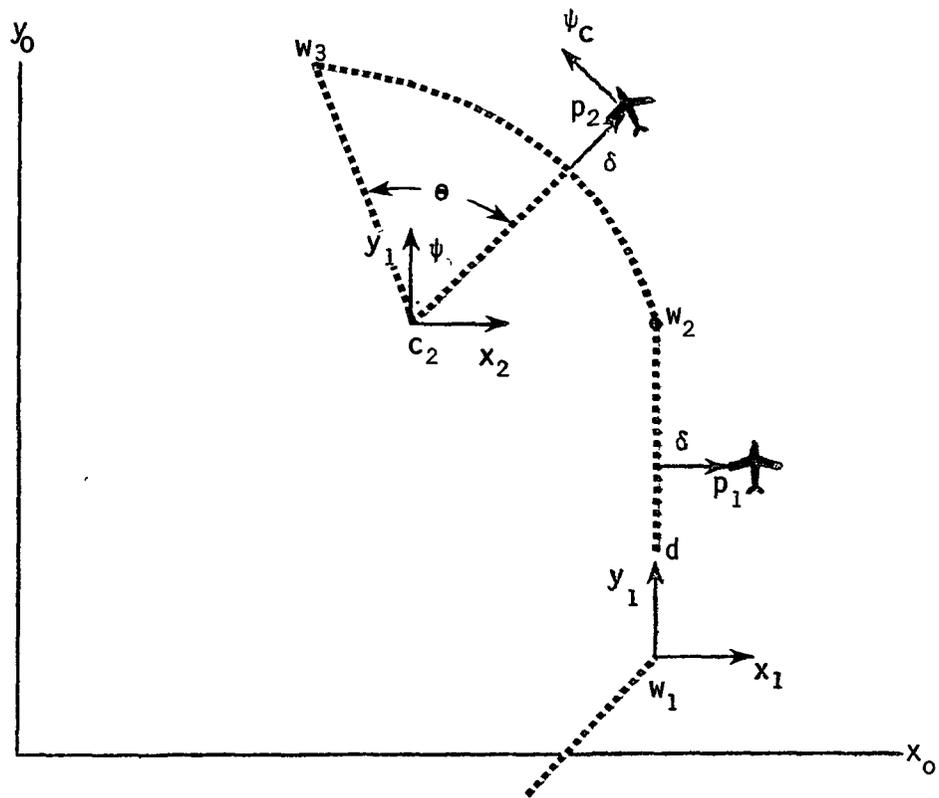
$$\psi_o = \psi_c + \alpha \pi / 2$$

$$\phi_o = \frac{\alpha V^2}{gR}$$

where  $\psi_c$  is the bearing of the aircraft relative to the computational reference frame and  $\alpha$  is a normalized parameter indicative of the direction of turn. The constant  $\alpha$  is defined by

$$\alpha = (w_3 \times w_2) / |w_3 \times w_2|$$

where  $w_2$  and  $w_3$  are respectively the initial and final waypoint vectors (see Figure 4.2) of the arc segment. The curved segment is concluded when the



- $x_0, y_0$  - runway centered coordinate axes
- $x_1, y_1$  - coordinate axes for straight - line segment
- $x_2, y_2$  - coordinate axes for arc segment
- $p_1, p_2$  - aircraft positions relative to nominal flight path
- $d$  - distance to complete straight-line segment
- $\theta$  - angle to complete arc segment
- $w_1, w_2, w_3$  - initial waypoint vectors
- $c_2$  - center of curvature for arc segment

Figure 4.2 Guidance System Reference Frames

aircraft flight path intersects the line defined by the segment endpoint,  $w_3$ , and the center of curvature,  $c_2$ .

#### 4.1.3 Sensor Errors

To evaluate the impact of measurement errors on the precision of executing a curved approach path, the modeling of measurement error effects was considered in the simulation development. Since the integration of the aircraft equations of motion was performed in the computational reference frame related to the current flight segment, the inclusion of errors in the measurement of MLS-derived range, azimuth, and elevation required the transformation from the computational to the runway-centered coordinate system and back. At each step of the integration cycle the aircraft state was converted to the MLS reference frame by the linear transformation:

$$x_r = Tx_c + v$$

where the matrix  $T$  and the offset vector  $v$  were defined earlier for both the straight-line and arc segment cases. In the runway-centered system the errors are additive:

$$\hat{x}_r = x_r + e_r$$

where the error vector  $e_r$  was either considered as a fixed bias or a random variable derived from a Gaussian white noise process. The noise-corrupted state is then transformed back to the computational reference frame by:

$$\hat{x}_c = T' (\hat{x}_r - v)$$

where  $T'$  indicated the transpose of the matrix  $T$ . The resulting measured aircraft state,  $\hat{x}_c$ , is then processed by the navigation and control equations to derive the required flight control parameters.

#### 4.1.4 Wind Effects

Another consideration in the evaluation of curved approach procedures was the effect of wind on the aircraft's ability to maintain a precise ground track.

If the bank angle command required to execute a curved path were computed on the basis of the nominal groundspeed, then, assuming that a constant airspeed is maintained, the lateral-axis component of the wind would cause the aircraft to deviate from the desired arc. Thus it was considered appropriate to model this disturbance phenomena to gain an assessment of the degree of track error encountered in this situation. However, since the aircraft was considered as a point mass in the development of the simulation, certain simplifying assumptions had to be made to include the effect of the wind in this formulation. Perhaps the most restrictive premise was the assumption that an accurate measurement of aircraft heading was provided to enable the aircraft to counter the cross-axis effect of the wind. If this control capability were not assumed, the point mass description of the aircraft motion would not be applicable. The second assumption was that a constant airspeed was maintained along the approach path. In the disturbance free case the lateral motion of the aircraft is derived from the integration of the following state equations:

$$\begin{aligned}\dot{x} &= v_x \\ \dot{y} &= v_y \\ \dot{v}_x &= v_y \dot{\gamma} \\ \dot{v}_y &= v_x \dot{\gamma}\end{aligned}$$

where  $\gamma$  is the aircraft heading. In this case, the airspeed

$$v_a = (v_x^2 + v_y^2)^{\frac{1}{2}}$$

is equivalent to the groundspeed and constant. If the wind is constant and defined by a velocity magnitude and direction  $(v_w, \beta)$ , then the aircraft velocity components are determined by:

$$\begin{aligned}v_x &= [V_a + V_w \cos(\gamma - \beta)] \sin \gamma \\ v_y &= [V_a + V_w \cos(\gamma - \beta)] \cos \gamma\end{aligned}$$

and the velocity derivatives are given by

$$\begin{aligned}\dot{v}_x &= [v_y - V_w \sin(\gamma - \beta) \sin \gamma] \dot{\gamma} \\ \dot{v}_y &= [-v_x \dot{\gamma} - V_w \sin(\gamma - \beta) \cos \gamma] \dot{\gamma}\end{aligned}$$

The simulation was modified accordingly to include the effect of the wind and several test cases were exercised.

#### 4.1.5 Simulation Exercises

The aircraft guidance system model described in Section 4.1 was exercised to determine the degree of precision expected in executing both the linear segment and arc segment noise abatement approaches to runway 18 at Washington National. The guidance gain parameters ( $K_\delta$  and  $K_\psi$ ) computed in the previous section (Table 4.1) were intended to apply to a light twin aircraft. Specifically the design constraints were based on observations of flight tests involving an Aero Commander 500. Thus it was appropriate to also consider the effect of selecting gains representative of a commercial jet aircraft. Since the design of the TCV guidance control law was very similar to that of the light twin model, it was appropriate to adopt the gains specified in the documentation of the Boeing-developed AGCS [Reference 30]. In this report the control law gains are given by:

$$K_\psi = \frac{V}{57.3} K_V$$

$$K_\delta = \frac{57.3g}{V^2} K_\psi^2$$

where

$$K_V = \begin{cases} .5 & V_k < 100 \text{ Kt.} \\ .68 - .0018V_k & 100 \text{ Kt} \leq V_k \leq 300 \text{ Kt} \\ .14 & V_k > 300 \text{ Kt} \end{cases}$$

The values of the TCV gain constants at 62 m/s (120 Kt) are:

$$K_\psi = 1.64$$

$$K_\delta = 9.91 \times 10^{-2} \text{ deg/m} \quad (3.02 \times 10^{-2} \text{ deg/ft.})$$

The aircraft system model was exercised with both the light twin and TCV guidance system gains for several different error cases to determine if the system could achieve the accuracy consistent with the width of the corridor defined by the

boundaries of the Potomac River. The test cases considered include:

- Linear segment approach with light twin gains
- Linear segment approach with TCV gains
- Arc segment approach with light twin gains
- Arc segment approach with TCV gains
- Arc segment approach with  $\pm 30$  m ( $\pm 100$  ft) range error
- Arc segment approach with  $\pm .1$  deg azimuth error
- Arc segment approach with 10 m/s (20 kt) westerly wind

The results for each of these test cases are presented in Section 5.1.

#### 4.1.6 TCV Implementation and Flight Test

The program structure of the AGCS is such that the facility for executing curved approach paths could be easily achieved by modifying the waypoint notation defining each arc segment. Instead of the initial and center-of-turn waypoint specification, the arc segment is determined by the desired turn radius and the inbound and outbound tangents to the arc. The tangents are indirectly specified by consecutive waypoints not necessarily coincident with the desired flight path. The details of this notation are discussed in a following section.

The simulation experiments previously presented are not sufficient to determine the practicality of curved approaches in a realistic environment and thus more detailed simulations of aircraft exercising curved paths are certainly appropriate. However, the critical issue of the flight crew's reaction to a non-standard approach procedure can only be resolved by subjecting pilots to the actual situation under realistic flight conditions. Thus, it is suggested that a flight test be conducted at the FAA's National Aviation Facilities Experimental Center where MLS coverage is available to provide guidance along a curved approach path. The objectives and planned tests to accomplish this exercise are discussed further in Section 7.1.

## 4.2 ANALYTICAL APPROACH - ENERGY MANAGEMENT

A number of previous studies on energy optimization have used optimal control theory as the basis for the analysis [References 31 and 32]. These analyses have usually been applied to military aircraft where the constraints described in the previous section are less restrictive. For civil aircraft operating in an air traffic control environment with conventional flight instruments, the constraints are sufficiently restrictive so that a more direct approach to energy management optimization is more practical than the theoretical approach. The approach that was selected consists of constructing a computer model of specific aircraft which will accurately compute performance characteristics of the aircraft such as time to altitude, distance to altitude, fuel to altitude, rate of climb or descent, specific range, etc. The model was constructed to predict performance values for a wide range of speed and altitude conditions and to be able to climb, descend, accelerate and decelerate the aircraft according to various control laws to permit time and fuel comparisons to be made.

Performance models of two aircraft were selected for development. The first aircraft selected was the Boeing 737-200 twin-engine, turbofan-powered aircraft. This aircraft is representative of a small, short-haul aircraft that is found in the civil fleet. This aircraft was selected as one of the aircraft to be analyzed because the performance data obtained from the model could be directly validated by flight test data which could be collected from the NASA Terminal Configured Vehicle (TCV) aircraft. The flight instrumentation and data recording capabilities of the TCV aircraft are quite compatible with the data which can be collected from the performance model.

The second aircraft that was selected for performance model development was the McDonnell Douglas DC-10-10. The DC-10-10 is a wide body aircraft with three General Electric CF6-6D1 turbofan engines. This aircraft is representative

of a large, medium to long range aircraft that is found in wide use throughout the airline industry. The use of the DC-10-10 and the B737-200 for performance analysis provides a broad range of turbofan aircraft which generally brackets those airline aircraft in commercial use at the present time in the U.S.

#### 4.2.1 Model Description

A number of aircraft models of varying degrees of sophistication are possible candidates for performance assessment. Schultz and Zagalsky [Reference 31] discuss five models which are suitable candidates for aircraft description for this study. They are:

- flight path moment equations
- point mass equations
- point mass - small angle-of-attack approximation
- point mass - equilibrium of vertical forces - small flight path angle
- energy state approximation

In reviewing the available performance data and the data collection requirements, it was determined that the point mass - small angle of attack approximation equations would best fill the requirements for the aircraft model. A force diagram of the aircraft model is shown in Figure 4.3. The equations of motion for the aircraft reduce to:

$$dV/dt = (T-D)g/W - g \sin \gamma \quad (4.7)$$

$$dx/dt = V \cos \gamma \quad (4.8)$$

$$dh/dt = V \sin \gamma \quad (4.9)$$

$$dw/dt = f (T,V,H,P) \quad (4.10)$$

where  $V$  = true airspeed  
 $T$  = thrust  
 $D$  = drag  
 $W$  = aircraft weight

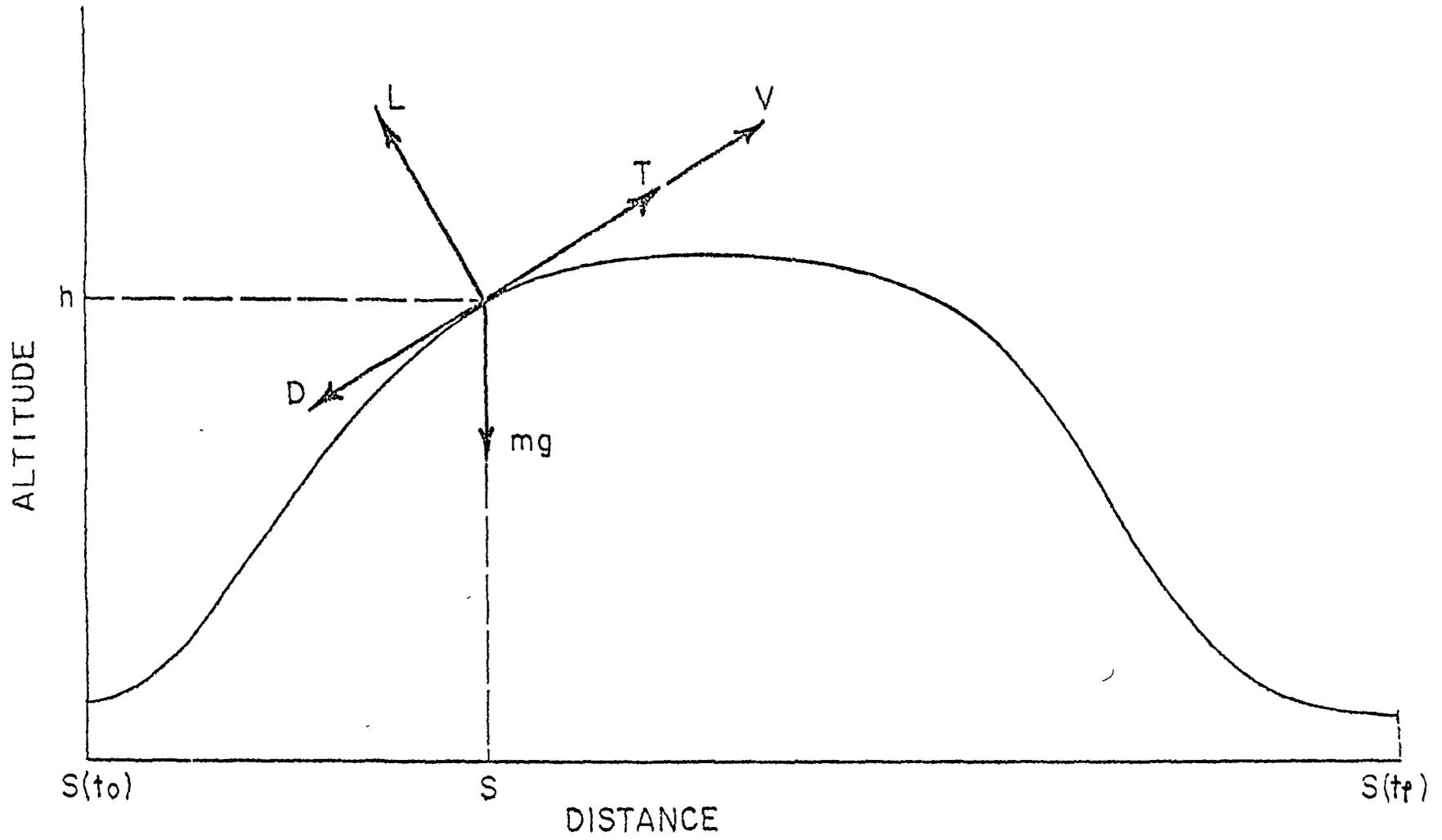


Figure 4.3 RELATIONSHIP OF SYSTEM VARIABLES

- g = gravitational constant
- $\gamma$  = flight path angle
- X = horizontal distance
- H = altitude
- f = functional expression for fuel flow
- P = power ratio
- t = time

The drag expression is made up of a profile drag and an induced drag term.

$$D = qS (C_{D0} + C_{DI})$$

- where
- q = dynamic pressure
  - S = aircraft wing area
  - $C_{D0}$  = profile drag coefficient
  - $C_{DI}$  = induced drag term

The profile drag term is assumed to be constant throughout the flight envelope. The induced drag term is computed from the aircraft lift coefficient:

$$C_{DI} = C_L^2 / (\pi \cdot AR \cdot e)$$

- where
- $C_L$  = lift coefficient
  - $\pi$  = 3.14159...
  - AR = aspect ratio of wing
  - e = wing efficiency

The lift coefficient is determined by assuming that the aircraft is in equilibrium in the direction normal to the thrust and drag vectors. Hence,

$$L = W \cos \gamma$$

and  $C_L = L/qS$

The dynamic pressure q is calculated from the expression

$$q = \frac{1}{2} \rho v^2$$

where  $\rho$  = the density of air using the ICAO standard atmosphere. Other velocity parameters such as indicated airspeed and Mach number are computed from true airspeed using the ICAO standard atmosphere.

#### 4.2.2 Engine and Airframe Parameters

The terms in the equations of motion which require further definition include the thrust, drag, flight path angle and the functional relationship for fuel flow. The most readily available source of aircraft performance information is contained in performance handbooks for the Boeing 737-200 and the DC-10-10 [References 33 and 34]. The data that was available for the DC-10 included the following types of information:

##### Climb Data

1. Time to altitude
2. Distance to altitude
3. Fuel to altitude
4. Rate of climb vs altitude
5. High speed climb and long range climb for various aircraft weights

##### Cruise Data

1. Specific fuel consumption as a function of aircraft speed, altitude and weight

##### Descent Data

1. Time to descend
2. Distance to descend
3. Fuel to descend
4. High speed descent and long range descent for various aircraft weights

The data that was available for the B737-200 was slightly less comprehensive than that for the DC-10 aircraft. Rate of climb information was not available in this performance handbook. In addition, the data was presented in tabular form rather than in charts as was the case of the DC-10-10. The resolution of the tabular data was rounded to the nearest whole minute of climb data, the nearest whole nautical mile for distance data and the nearest hundred pounds for

the fuel data. This lack of resolution presented some problems in converting the data to a form that was useful in the performance model. The steps that were taken in circumventing this problem will be discussed in a subsequent paragraph.

The first term that was computed from the performance data was the profile drag term,  $C_{D0}$ . This parameter was computed from climb and cruise data taken at the same air speeds. An assumption was made that the aircraft thrust is proportional to fuel flow for a given Mach number. This permitted the engine thrust ratio to be computed for the cruise case. The fuel flow during climb was computed from a ratio of the derivative of the fuel to climb curve divided by the derivative of the time to climb curve. Although the fuel flow can only be estimated from this procedure the results were sufficiently consistent to permit a value to be determined for the  $C_{D0}$  term. In performing these calculations some estimates of the wing area, aspect ratio and wing efficiency were necessary. In the case of the DC-10-10 the wing area and the aspect ratio were given in the performance data. For the Boeing 737-200 these parameters were determined from scale drawings of the aircraft. The wing efficiency for aircraft of this type generally runs between 75% and 80%. Consistent results were obtained by using values in this range.

Once the profile drag term has been computed it is possible to reexamine the climb data and compute the maximum continuous thrust and fuel flow as a function of altitude. This computation can be made for several different weights of aircraft and the results compared directly since the aircraft thrust does not change as a function of aircraft weight. Since both high speed and long range climb profile data was available for both aircraft, the thrust and fuel flow values for maximum continuous thrust could be computed at two different airspeeds or Mach numbers for each altitude. It is thereby possible to compute thrust and fuel flow values at other speeds by interpolating between the two curves.

It was stated in a previous paragraph that a fundamental assumption in the development of the performance model was that the aircraft thrust was proportional to fuel flow for a specified Mach number. This relationship was determined by examining the specific range or fuel flow data under cruise conditions. During cruise, thrust is identically equal to the drag, which permits the thrust to be calculated from those parameters which have been determined previously. The fuel flow can be determined from specific range data. Consequently, the ratio between fuel flow and thrust can be determined for a wide range of speed and altitude conditions. This data was plotted as a function of aircraft Mach number and a second degree polynomial curve fit was determined. The data shown in Figure 4.4 shows the resulting data points and the second degree polynomial fit.

The one remaining area of the model that needed to be completed at this point was to determine the engine thrust at flight idle for use during descent. In the case of the DC-10-10 the data during descent was fairly specific as to what the speed and throttle settings were during the descent. In this case a procedure for determining descent thrust and fuel flow was used which was exactly analogous to the computation of the climb fuel flow and thrust which was discussed in an earlier paragraph. In the case of the B737-200 it was necessary to make some assumptions concerning the descent conditions. The speeds and descent rates given for this aircraft were only approximate values. Consequently, an assumption was made that the idle thrust is approximately 10% of the full thrust value. This assumption was implemented in the B737 model and the result compared quite favorably with the limited amount of descent data that was available in the operational handbook. It was therefore considered to be sufficiently accurate to permit valid comparisons to be made for different types of descent procedures for the Boeing 737 aircraft.

#### 4.2.3 Development of Profile Controls

In examining the equations of motion for the performance model it was

Configurations

Alt. [Km(ft)], Wt [1000 Kg(1000 lb)]

$$T = K(M) * FF$$

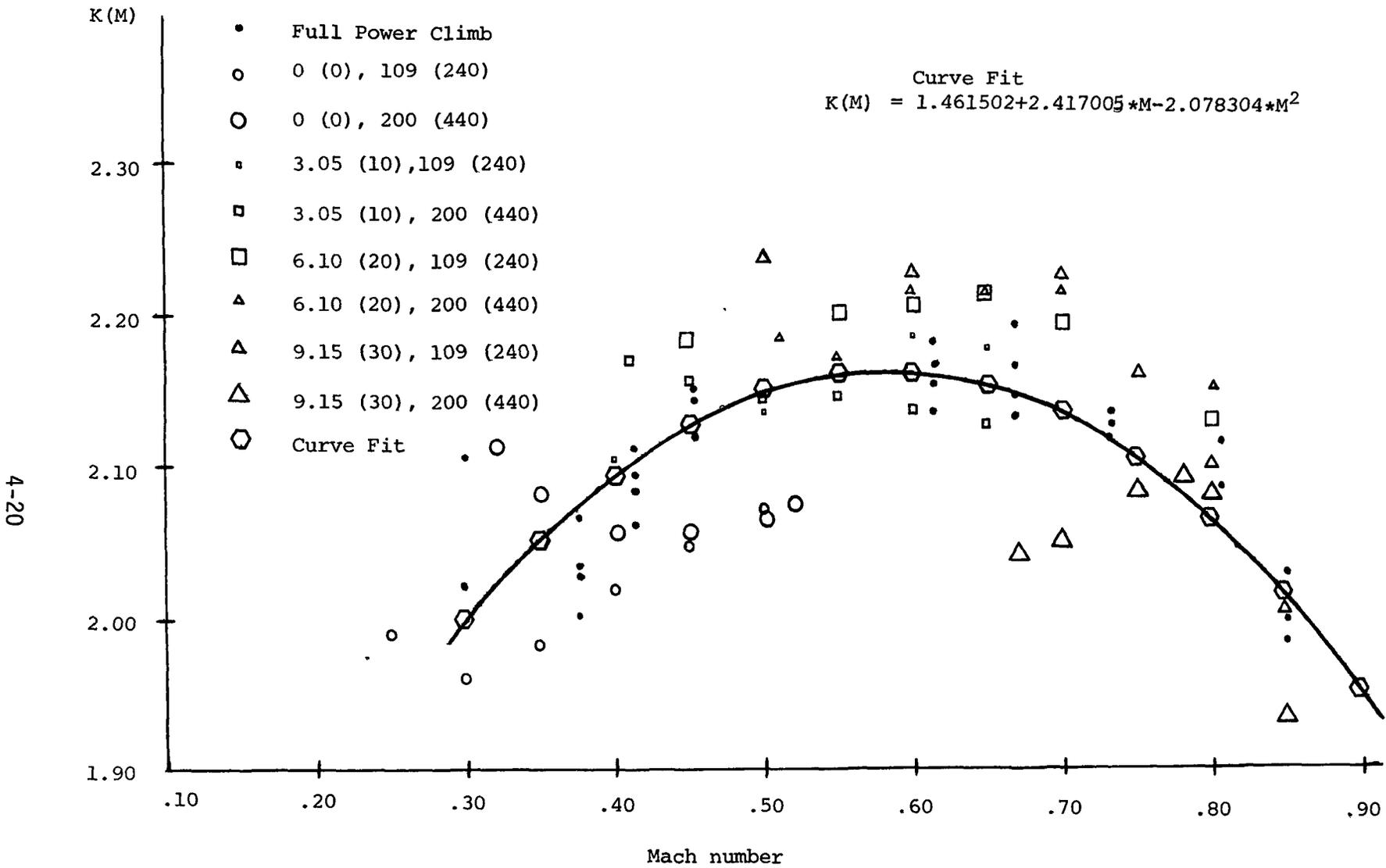


Figure 4.4 Second Order Curve Fit to Thrust/Fuel Flow Ratio vs. Mach Number

determined that the most suitable candidates for controlling the profile of the aircraft were thrust and flight path angle. A control mode structure was developed for the model around varying these two parameters to produce the desired profile. In addition it was often desirable to be able to adjust the speed of the aircraft in order to produce the desired profile. Consequently, it was necessary in many instances to relate the aircraft speed or speed changes to thrust and/or flight path angle. A series of six control modes were developed for the performance model. These six control modes are as follows:

1. Constant Flight Path Angle-Full or Idle Thrust
2. Constant D(IAS)/DH-Full or Idle Thrust.
3. Constant D(Mach)/DH-Full or Idle Thrust.
4. Constant Flight Path Angle-Constant Indicated Air Speed.
5. Constant Flight Path Angle-Constant Mach Number.
6. Constant Rate of Climb/Descent-Full or Idle Thrust.

In addition to the control mode structure two more profile control variables were used as input data. The first is a flight phase indicator. In flight phase one, which is the climb phase, either full or throttled thrust can be requested. However, the throttled thrust value must be greater than the idle thrust values. During flight phase two, which is representative of cruise, any thrust value between full thrust and idle thrust may be selected. Finally, during flight phase three or descent, only throttled or idle thrust may be selected. It is possible to change between flight phases at specified points in the aircraft profile.

The one remaining aspect of aircraft profile control that was implemented in the performance model was the ability to change between control modes and/or flight phases at specified points in the profile. This point is determined by selecting one of five stop parameter values. When the model reaches one of these stop parameter values during the generation of the profile, a new set of

flight phase, control mode and stop parameters are established for the performance model. These stop parameters are as follows:

1. Altitude
2. Indicated Airspeed
3. Mach Number
4. Distance
5. Incremental distance

When a complete set of control modes, flight phases and stop parameters have been processed by the model, the computer run is terminated and the next case is initiated.

In the first control mode the derivative values for the equations of motion are easily determined from the input data. In this control mode the flight path angle is determined from input data and the thrust level is determined by the flight phase indicator. Consequently, all of the derivatives and the lift and drag values can be computed directly.

In the second and third control modes the determination of derivative values and the lift values are considerably more complicated. In these modes the rate of change of either indicated airspeed or Mach number changes linearly with altitude. The thrust value is set at either full or idle thrust depending on the flight phase indicator. However, the solution for the flight path angle requires an in depth examination of the relationships between the speed derivative and the expressions for the aircraft lift. A functional relationship between true airspeed and indicated airspeed can be shown by the following expression: .

$$V_T = f(V_I, H, T_D)$$

Where  $V_T$  = true airspeed

$V_I$  = indicated airspeed

$H$  = altitude

$T_D$  = temperature deviation from standard

By differentiating this expression with respect to time, an expression for the aircraft acceleration in terms of the rates of change of indicated air-speed can be established. This is shown in the following expression:

$$\frac{dV_I}{dt} = \frac{\partial f}{\partial V_I} \frac{dV_I}{dt} + \frac{\partial f}{\partial H} \frac{dH}{dt} + \frac{\partial f}{\partial T_o} \frac{dT_o}{dt}$$

$$\text{where } \frac{dV_I}{dt} = \frac{dV_I}{dH} * \frac{dH}{dt} = \text{Control} * \frac{dH}{dt}$$

CONTROL = the input control value also, for a standard atmosphere

$$\frac{dT_o}{dt} = 0$$

Consequently, the acceleration can be expressed in the following manner:

$$\frac{dV_I}{dt} = \left[ \left( \frac{\partial f}{\partial V_I} * (\text{CONTROL}) + \frac{\partial f}{\partial h} \right) \right] * \frac{dH}{dt}$$

$$\text{or } \frac{dV_I}{dt} = K_v * \frac{dH}{dt}$$

$$\text{where } K_v = \frac{\partial f}{\partial V_I} * (\text{CONTROL}) + \frac{\partial f}{\partial h}$$

This expression may be equated to Equation 4.7 of the aircraft equations of motion. Equation 4.9 can be substituted into Equation 4.7 and yield the following expression:

$$K_v * V \sin \gamma = \frac{(T-D)}{W} g - g \sin \gamma$$

All values in this expression are now known except the drag term D and the flight path angle term  $\gamma$ . However, D can be related to the flight path angle through the lift equation. The resulting expression for drag is:

$$D = \left[ \left( C_{D0} + \left( \frac{W}{qS} \right)^2 \frac{(1 - \sin^2 \gamma)}{\pi \cdot e \cdot AR} \right) \right]$$

When substituted into the previous expression, the following quadratic expression is obtained for  $\sin \gamma$ :

$$0 = \sin^2 \gamma \frac{gW^2}{\pi \cdot e \cdot AR \cdot q \cdot s} - \sin \gamma [W(K_V \cdot V = g) + ](T - q s C_{D0} - \frac{W^2}{\pi \cdot e \cdot AR \cdot q s} g]$$

The quadratic expression yields two values for  $\sin \gamma$ ; however, one value is greater than unity and can thus be eliminated. Now that both  $\gamma$  and the thrust have been determined, it is possible to calculate the remaining derivative values for the equations of motion. The preceding derivation has been performed for the constant rate of change of indicated airspeed with respect to altitude. An exactly analogous situation occurs in the case of the constant rate of change of Mach number with respect to altitude. The only difference is that the functional relationship between true airspeed and Mach number is used rather than the functional relationship between true airspeed and indicated airspeed.

The next two control mode cases concern the constant flight path angle with either constant indicated airspeed or constant Mach number. Since the flight path angle is constant, it is a known input quantity. Consequently, in order to maintain the constant speed it is necessary to adjust the thrust accordingly. This is done by making use of the  $K_V$  quantity or the  $K_M$  quantity that was used in the previous control mode discussion. The  $K_M$  quantity is analogous to  $K_V$  except that the Mach number function is used. The thrust value can be determined by equating the two terms for the aircraft acceleration, the first coming from the functional relationship between true airspeed and either indicated airspeed or Mach number, and the second expression coming from the equations of motion of the aircraft. The resulting expression for the thrust required is shown in the following expression:

$$T = \frac{W}{g} (K_V V + g) \sin \gamma + D$$

This thrust value is then checked to determine that it is in the range between maximum continuous thrust and idle thrust. If this is not so, a comment is printed on the program output. Again the analogous situation exists for the constant Mach number, constant flight path angle case except that a  $K_M$  value is substituted for  $K_V$  in the previous expression.

The last control mode that was developed is the constant rate of climb or descent at full or idle thrust case. Since either full or idle thrust is used, this value is determined by the flight phase indicator. Since rate of climb or descent is constant, Equation 4.9 of the equations of motion can be solved for  $\sin \gamma$ . Consequently, both the thrust and the flight path angle are known and can be used in the other equations of motion.

These six control modes provide a sufficiently broad range of aircraft profile management to permit evaluation of a number of control techniques for climbing and descending aircraft.

#### 4.2.4 Model Validation

Upon the completion of the model development for the DC-10-10 and the B737-200 a validation phase of testing was initiated. Input data was prepared on the basis of providing a direct correspondence to the profiles that were contained in the performance handbooks. The models were exercised over two climb and descent profiles and three aircraft weights in order to check the correspondence between the model data and the handbook performance data. The model was also checked at a number of cruise data points to check the specific range values that resulted from the assumptions made in the model development. Minor adjustments were made in the thrust and fuel flow values to bring the profiles into closer alignment with the handbook performance values. The results of this validation task are contained in Section 5.

#### 4.2.5 Data Collection and Analysis

After the aircraft performance models were developed and validated a data collection task was initiated. The first data runs that were performed made use of standard climb and descent procedures. These procedures were used to form a base line data set from which subsequent tests could be compared. A wide variety of profiles including accelerating and decelerating climbs and descents were attempted. In addition some VNAV profiles and some constant rate of climb and descent profiles were obtained. The results in all cases were compared to the base line data sets. This type of analysis tends to null out minor discrepancies that may be contained in the performance model. For both the climb and the descent analysis, care was taken in order to be sure that the initial state and the final state of the aircraft were compatible such that an accurate determination of time and fuel benefits could be obtained.

Once the differences in time and fuel benefits were determined it was possible to then compute estimates of cost benefit associated with the variations in the performance profile. Cost data was collected from Civil Aeronautics Board (CAB) records [Reference 35 ]. A range of cost data was used to reflect a high and low operating cost to the user. The difference between the flight time cost for these aircraft is based upon the following:

- high hourly cost - total cost per flight hour less fuel
- low hourly cost - total cost per flight hour less fuel and depreciation.

A range of fuel cost was computed from values quoted by local suppliers and values appearing in recent publications [Reference 36 ]. The time and fuel benefits or penalties were then converted into cost by multiplying by the appropriate cost per flight minute and cost per pound of fuel. This permitted

the flight profiles to be evaluated both on an energy conservation and on an economic basis.

#### 4.2.6 Control System Design

Subsequent to the data collection and analysis task a technique was devised for implementing the previously described control modes into the actual aircraft or auto pilot system. The techniques were based upon the thrust and flight path angle control that were used in the aircraft model development. The control system design is intended to be used for collecting data to validate the results from the performance model in a flight test. The design may or may not be useful in actual airline aircraft due to limitations on the aircraft's present instrumentation and flight control equipment.

#### 4.2.7 Flight Test

The final task associated with this phase of the project was to prepare a set of flight tests which could be used to substantiate the results obtained from the performance model and to evaluate those parameters which were not considered in the performance model. The flight tests were designed around the instrumentation and data recording equipment that is available in the TCV aircraft. A set of parameters required for analysis of the flight test data is presented. The flight conditions such as recommended speeds, aircraft weight, control mode selection, control mode change points and cruise altitude are all stated in the recommended flight procedures. In addition, data analysis and data handling procedures are suggested in the flight test plan.

### 4.3 SUMMARY OF SECTION 4

A simulation approximating the dynamics of an aircraft and its lateral control system was developed to evaluate the precision of execution attainable along a curved approach path. Control law gains representative of both a light

twin aircraft and the TCV aircraft were evaluated. Also, the notation for defining the nominal curved path was discussed and the means to derive the guidance system error with respect to this nominal path were defined. A discussion of the approach to evaluate the effect of measurement errors and wind variation on the ground track achieved concluded the presentation on the approach to analyze curved paths.

A simulation model to compare the energy efficiency of alternative climb and descent procedures was presented. The model development was based on a point mass - small angle of attack approximation. The model parameters for thrust, drag, and flight path angle as well as the functional relationship for fuel flow were derived from the actual performance characteristics of a Boeing 737-200 and McDonnell-Douglas DC-10-10. Flight profile management was achieved by controlling aircraft thrust and flight path angle. Based on this configuration, six control modes were identified for evaluation.

## 5.0

## ANALYTICAL RESULTS

### 5.1 DCA CURVED APPROACH ACCURACIES

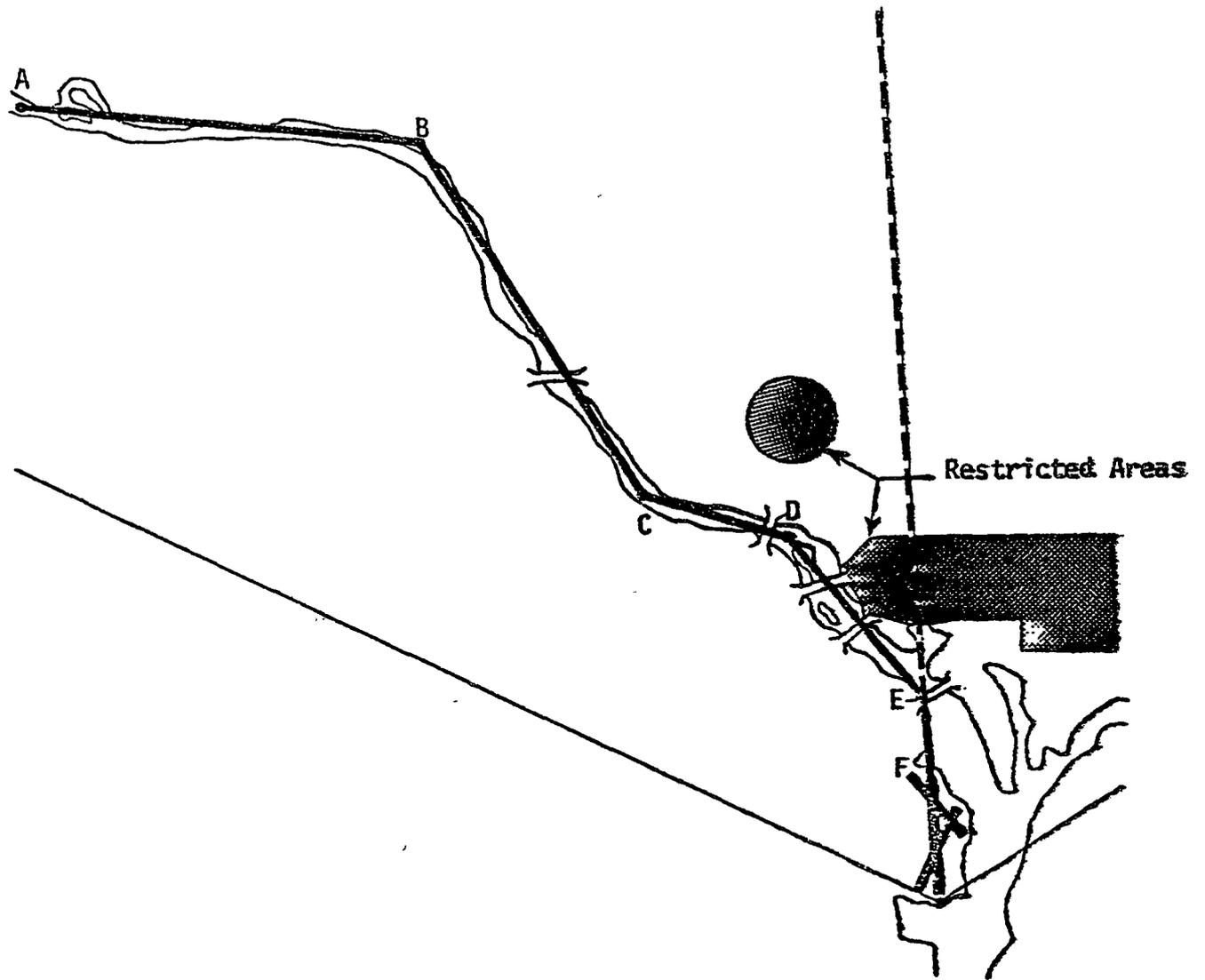
The test cases considered in the analysis of the curved approach procedure to Washington National include:

- Linear segment approach with light twin gains
- Linear segment approach with TCV gains
- Arc segment approach with light twin gains
- Arc segment approach with TCV gains
- Arc segment approach with  $\pm 30$  m ( $\pm 100$  ft) range error
- Arc segment approach with  $\pm .1$  deg azimuth error
- Arc segment approach with 10 m/s (20 kt) westerly wind

The results for each of these test cases are discussed in the following paragraphs.

#### 5.1.1 Linear Segment Approach

The cross track deviation resulting from the simulated flight along the linear segment (Figure 5.1) with the TCV guidance gains is shown in Figure 5.2. A positive deviation corresponds to a displacement of the aircraft to the right of the intended track. The dashed vertical lines of Figure 5.2 separate the segments shown in Figure 5.1. The segments labeled TURN correspond to the time intervals during which the aircraft executes a 3 deg/sec turn to intercept the following track. The graph of the deviation incurred with the light twin gains is not shown since its trace is nearly identical to that for the TCV gains. However, there was a significant difference in the magnitude of the peak deviations for the two cases. With the light-twin guidance gains, the cross track error exceeded 45 m (150 ft) while with TCV gains errors never exceed 23 m (75 ft). With the light twin gains, the oscillations following a track change are less pronounced since the gains were determined on the basis that the overall response be critically damped. As expected, both simulations demonstrated that the system tends to lag and overshoot the turn at a track change.



<u>Segment</u>	<u>Length, Km (nm)</u>	<u>Time, Sec, at 62 m/s (120 Kt)</u>
A-B	6.85 (3.70)	111.0
B-C	8.06 (4.35)	130.5
C-D	2.59 (1.40)	42.0
D-E	3.89 (2.10)	63.0
E-F	1.57 (0.85)	25.5

Figure 5.1 Linear Segment Approach to DCA - Runway 18

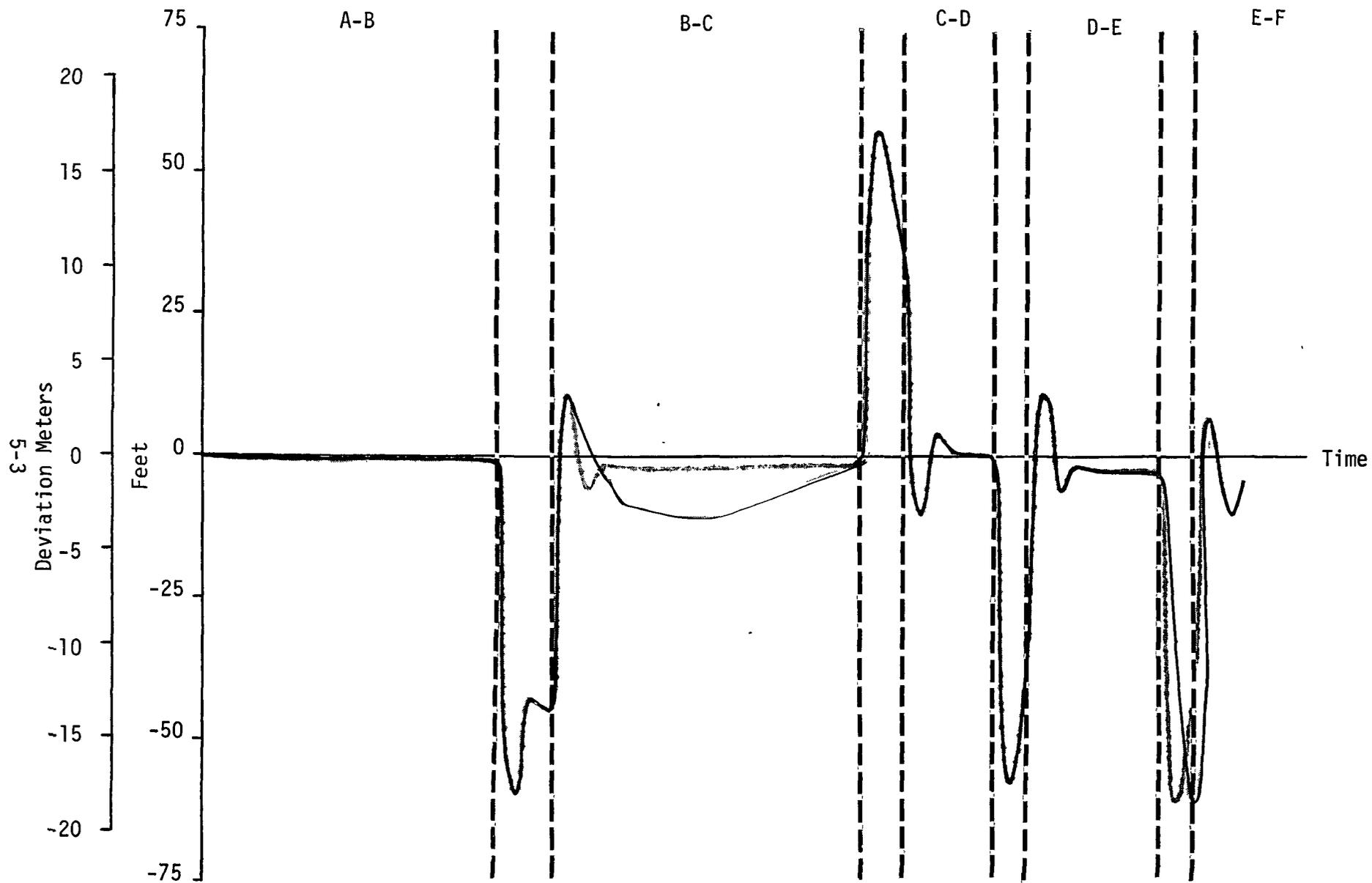


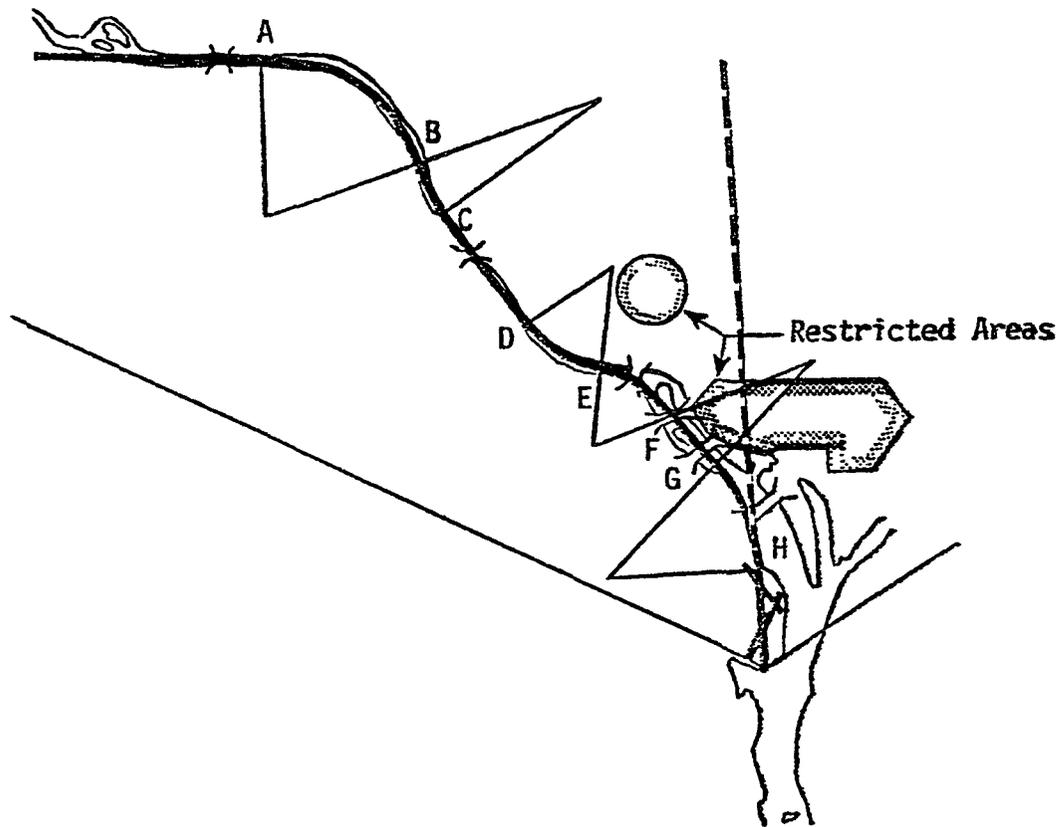
Figure 5.2 DCA Linear Segment Approach with TCV Gains

### 5.1.2 Arc Segment Approach

The plot of the cross track deviation experienced along the arc segment approach (Figure 5.3) is shown in Figure 5.4. Again, only the results for the simulation with the TCV gains is shown, since, except for the peak magnitudes, the response for the light twins's gains was nearly identical. In the latter case, the magnitude of the deviation exceeds 46 m (150 ft), while for TCV gains, peak deviations are less than 14 m (45 ft). Except for segment D-E following the straight-track, the tendency to overshoot the turn is evident. However, the peak deviations are less pronounced than those for the linear segment approach since the track changes are less abrupt. In both cases, the simulations demonstrated the capability of the guidance system to negotiate the curved approach without exceeding the limits of the river corridor.

### 5.1.3 Range Measurement Error

The path deviation resulting from a  $\pm 30$  m (100 ft) bias in the range measurement is plotted in Figure 5.5. The predominantly negative error can be explained with reference to Figure 5.6. Since the guidance system naturally tends to cause an overshoot of the turn, a negative flight path deviation was assumed in locating the actual position of the aircraft at point  $r$ . The positive range measurement bias results in a displacement of the measured position along the radius vector of the MLS coordinate system to the point  $r'$ . Initially one would assume that the increased track deviation would cause the aircraft to execute a tighter turn and thus overshoot the curved path. However, the heading error term in the guidance control law is more sensitive to the range measurement bias than the cross track deviation. Since the command heading is defined as the normal to the vector from the center of curvature to the measured position, the derived command heading  $\psi_o'$  lags the desired heading  $\psi_o$  and thus causes the aircraft to overshoot the turn. Although the effect is illustrated for a negative (clockwise) turn, the same rationale



<u>Segment</u>	<u>Radius, Km (nm)</u>	<u>Length, Km(nm)</u>	<u>Time, Sec, at 62 m/s (120 kt)</u>
A-B	3.61 (1.95)	3.87 (2.09)	62.74
B-C	4.20 (2.27)	1.37 (0.74)	22.06
C-D		3.19 (1.72)	51.68
D-E	2.28 (1.23)	1.65 (0.98)	29.42
E-F	1.93 (1.04)	1.91 (1.03)	30.83
F-G	3.63 (1.96)	1.52 (0.82)	24.72
G-H	3.50 (1.89)	2.59 (1.40)	41.85

Figure 5.3 Arc Segment Approach to DCA-Runway 18

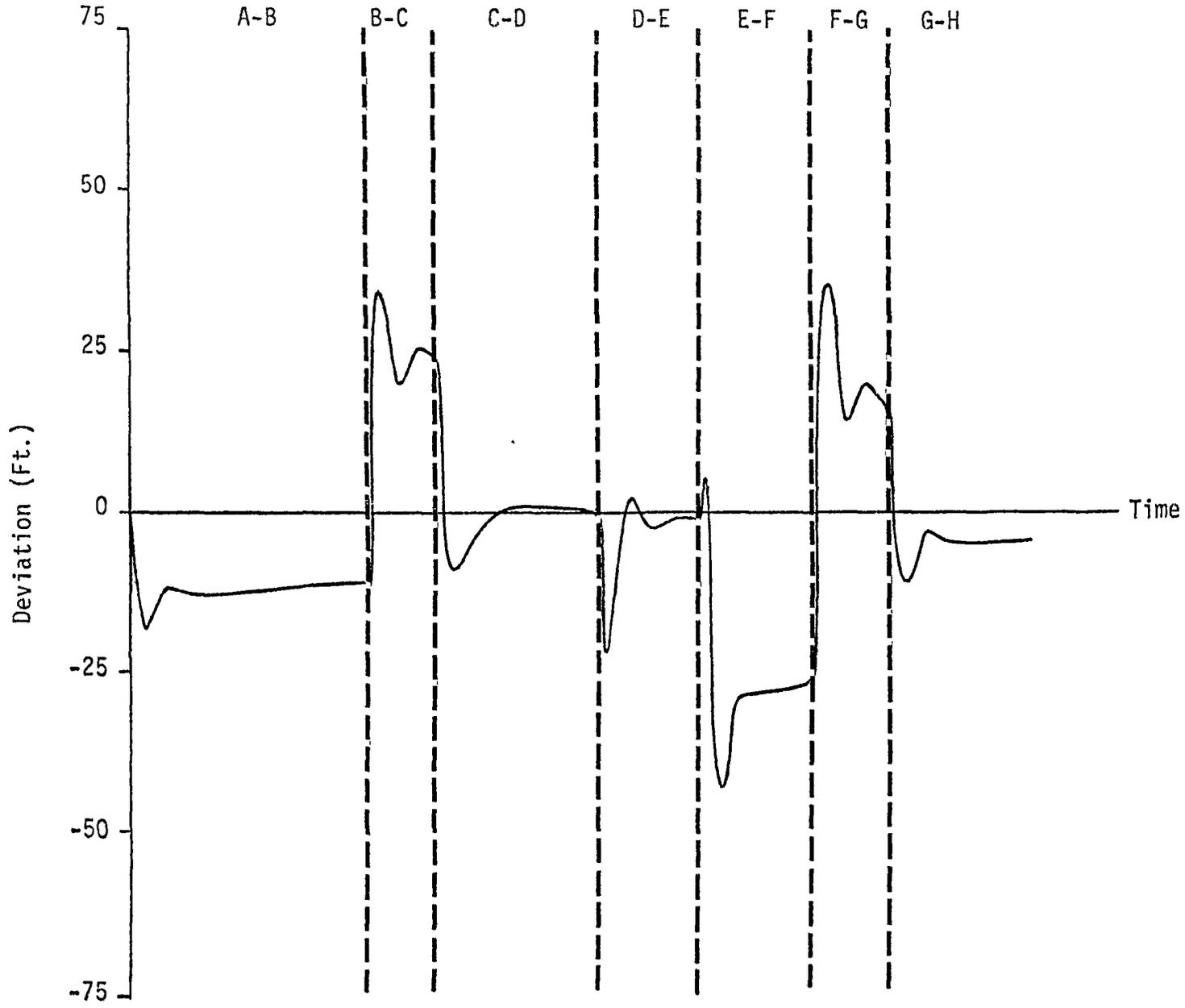


Figure 5.4 DCA Arc Segment Approach with TCV Gains

5-7

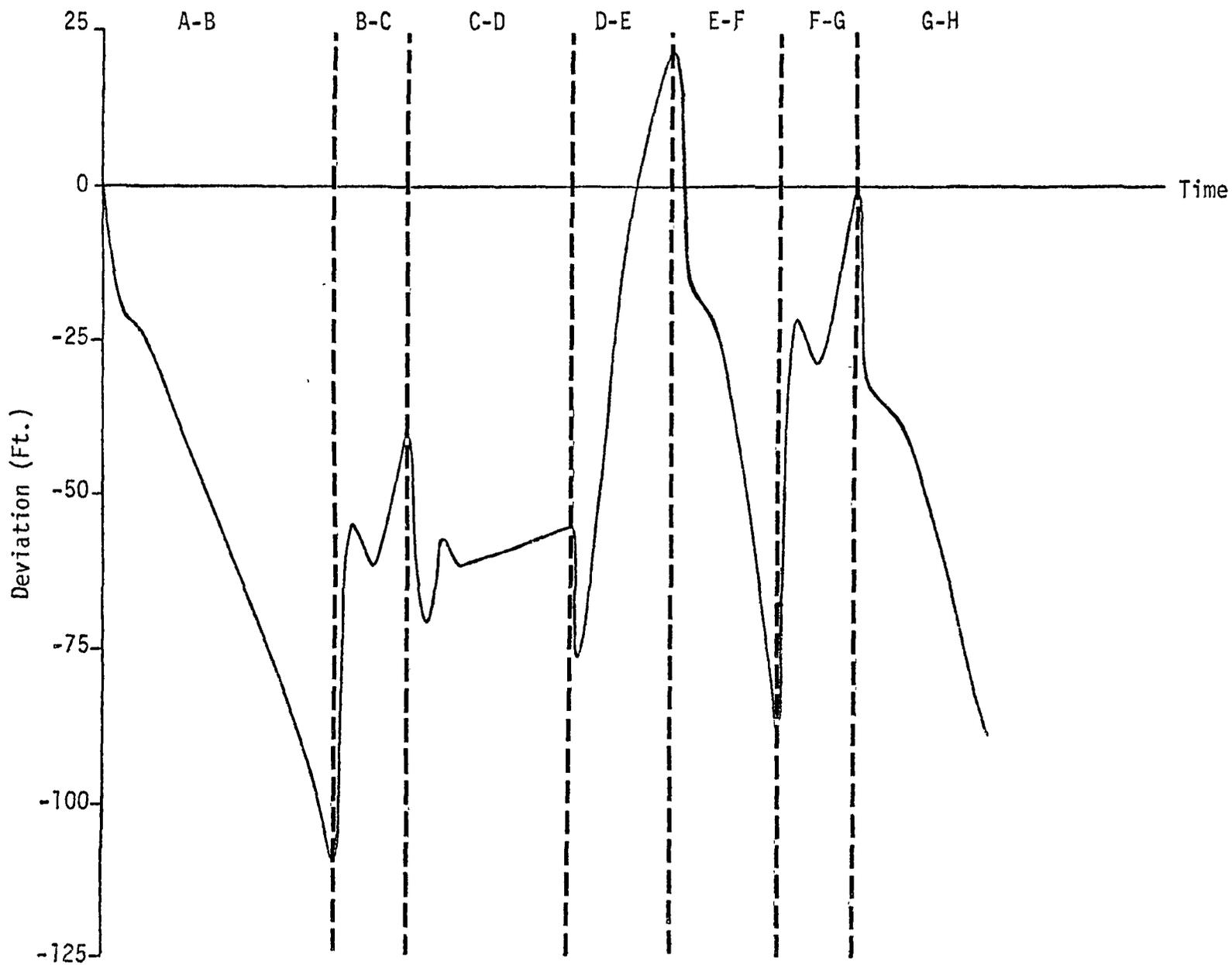


Figure 5.5 DCA Arc Segment Approach - 100 Ft. Range Bias

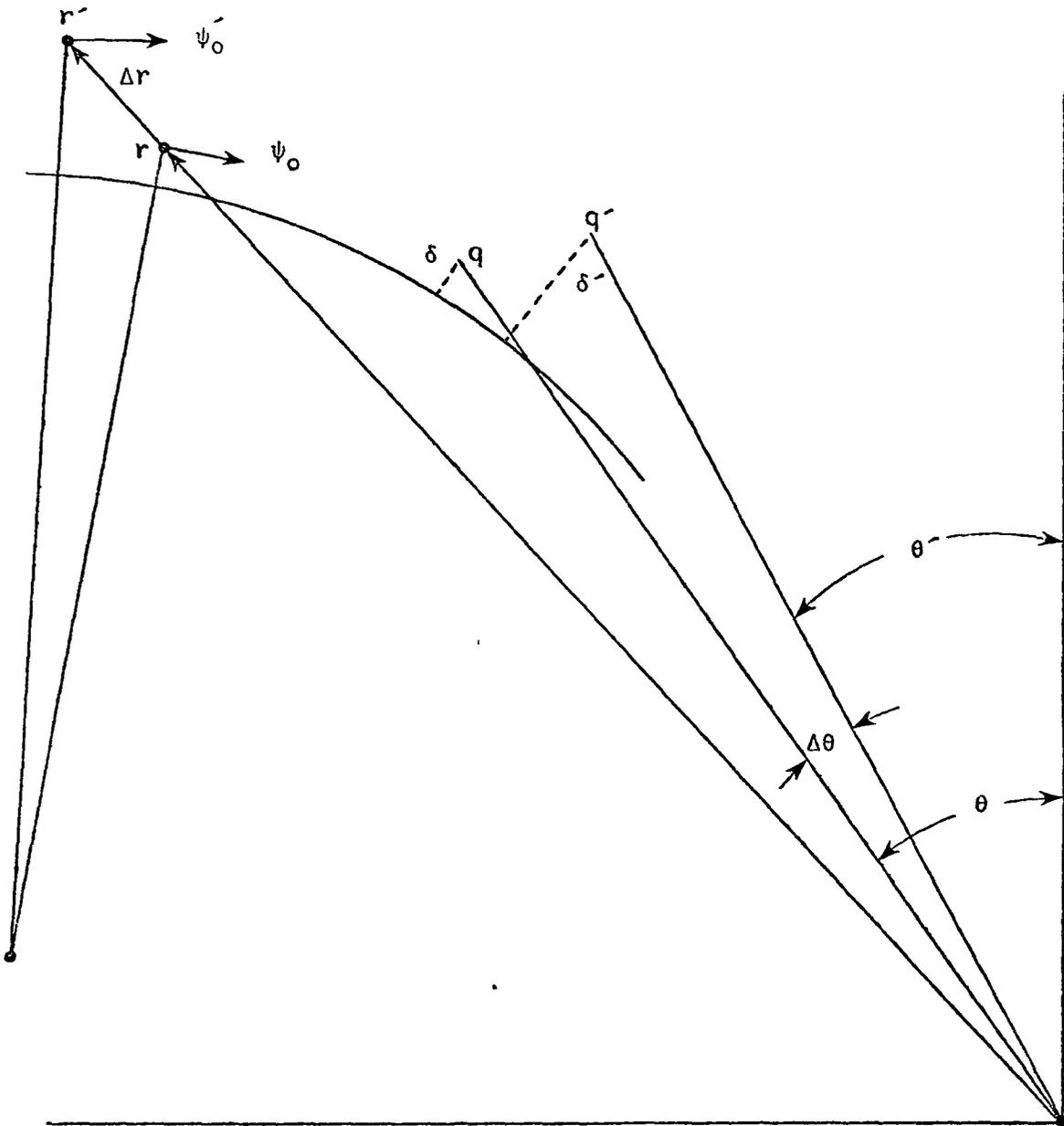


Figure 5.6 Error Effects of Range and Azimuth Biases

applies to the positive turn. A similar but opposite effect was noted for a negative range measurement bias. The negative error causes the command heading to lead the desired heading and thus results in an undershoot of the turn. However, in either case, deviations in excess of 100 ft. were rarely observed. Thus the effect of a range bias does not severely impact the ability of the guidance control law to command execution of the curved path.

#### 5.1.4 Azimuth Measurement Error

The aircraft guidance simulation was also exercised for the Washington National arc segment approach with a +.1 deg. azimuth measurement bias. The results of this exercise are shown in Figure 5.7. In this case the impact of the cross track deviation and not the heading error determines the net effect of an azimuth error. As shown in Figure 5.6, the bias results in a negative (left of flight path) displacement of the measured aircraft position to  $q'$  from the actual position at  $q$ . The decrease (increase in the magnitude) in the cross track deviation results in an increase of the bank angle command and thus causes the aircraft to undershoot the turn. The net effect is a positive (to the right of) displacement of the achieved track from the desired track. Again, a similar but opposite effect was noted with a negative azimuth measurement bias. The negative bias tends to reduce both the magnitude of the deviation and the bank angle command expected for the error-free case. The result is an overshoot of the desired track and a negative displacement of the track deviation curve. For both positive and negative measurement biases, the deviation from the nominal flight path barely exceeds 80 ft. Consequently, the effect of an azimuth measurement error should not hinder the execution of the curved approach.

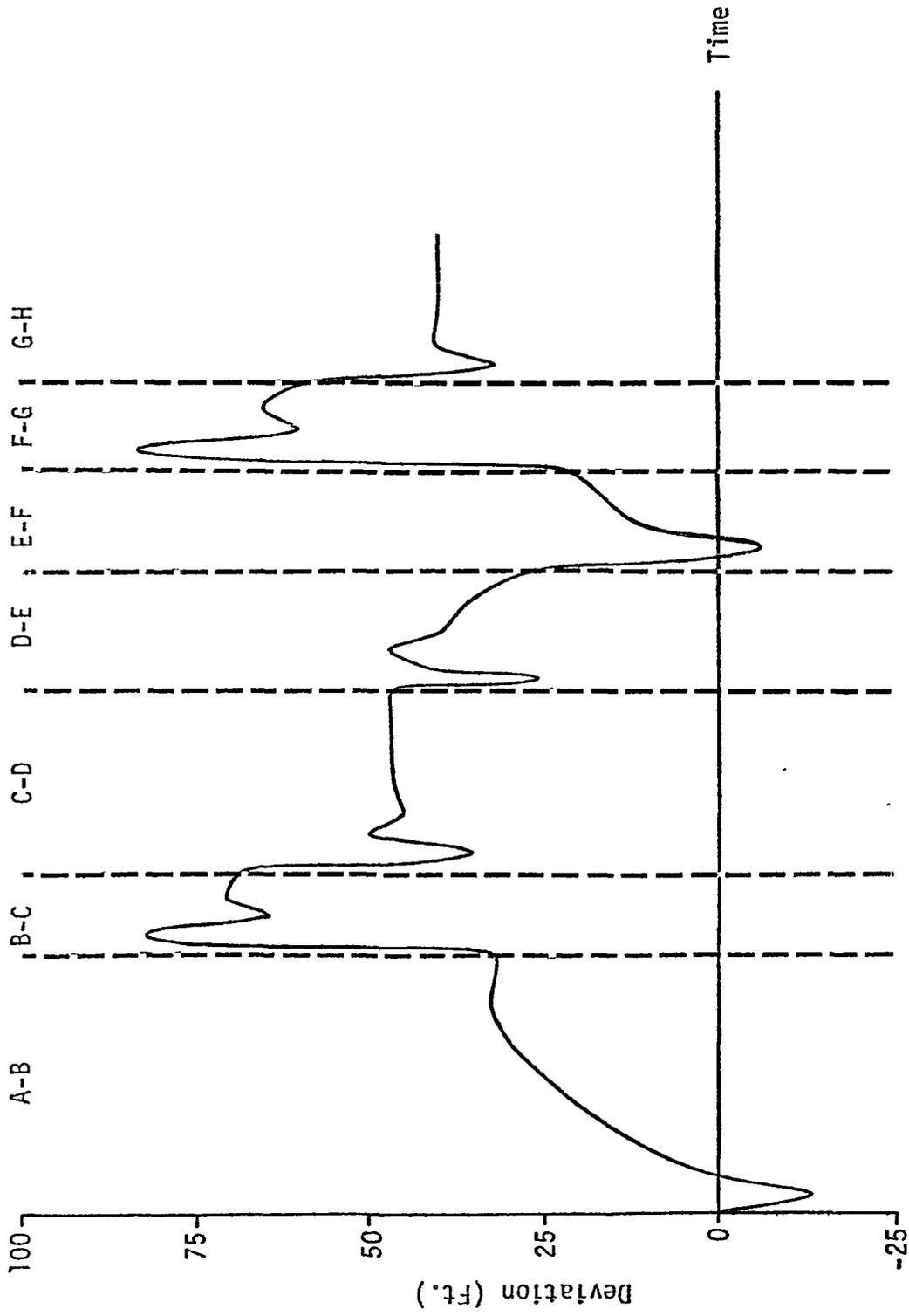


Figure 5.7 DCA Arc Segment Approach - 0.1 Deg. Azimuth Bias

### 5.1.5 Wind Effects

As discussed in Section 4.1, a simplified wind model was developed to gauge the effect of the longitudinal-axis component of the wind during a curved approach. Since the aircraft was modeled as a point mass, it was necessary to assume that the aircraft achieves the proper crab angle to counter the effect of the lateral-axis component. Also, it was assumed that a constant airspeed is maintained on approach and the wind velocity only affects the groundspeed. The impact of the wind on the achieved ground track is realized through the bank angle computation in the guidance control law. To maintain a constant-radius turn, the bank angle command must be responsive to changes in the groundspeed. The relationship between bank angle and groundspeed is approximated by

$$\phi_{\text{nom}} = \frac{V^2}{gR}$$

where  $V$  is the measured groundspeed and  $R$  is the desired radius of turn. Thus, if a constant bank angle is maintained and the groundspeed increases, the aircraft will overshoot the turn since the command signal applied to the control law is insufficient to maintain the desired turn radius. This effect was demonstrated by simulating the approach to Washington National with a 10 m/s (20 Kt) westerly wind. Since the general direction of the track is southeast, the westerly wind will tend to cause an overall increase in the groundspeed proportional to track heading. The nominal bank angle commands were determined by the measured groundspeed at the beginning of each arc segment and held constant through the turn. The resulting turn overshoot is apparent in the graph of the track deviation shown in Figure 5.8. ~~The impact of the wind can~~ be minimized by continuously computing the bank angle required to maintain the turn as a function of the groundspeed. The simulation was modified to include this capability and the results of the exercise are shown in Figure 5.9. For

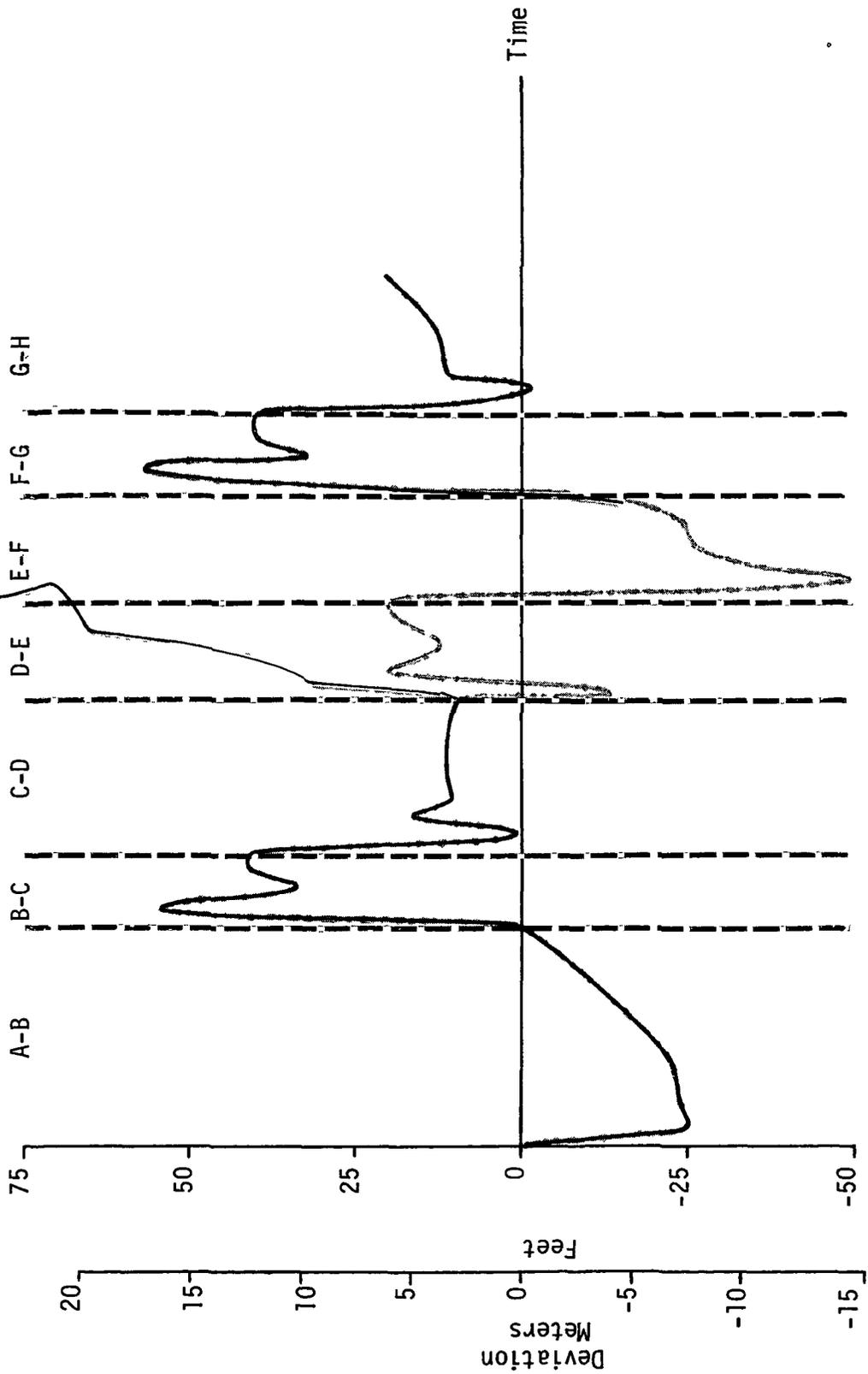


Figure 5.8 DCA Arc Segment Approach - 10.3 M/S (20 kt) Westerly Wind - Constant Bank Command

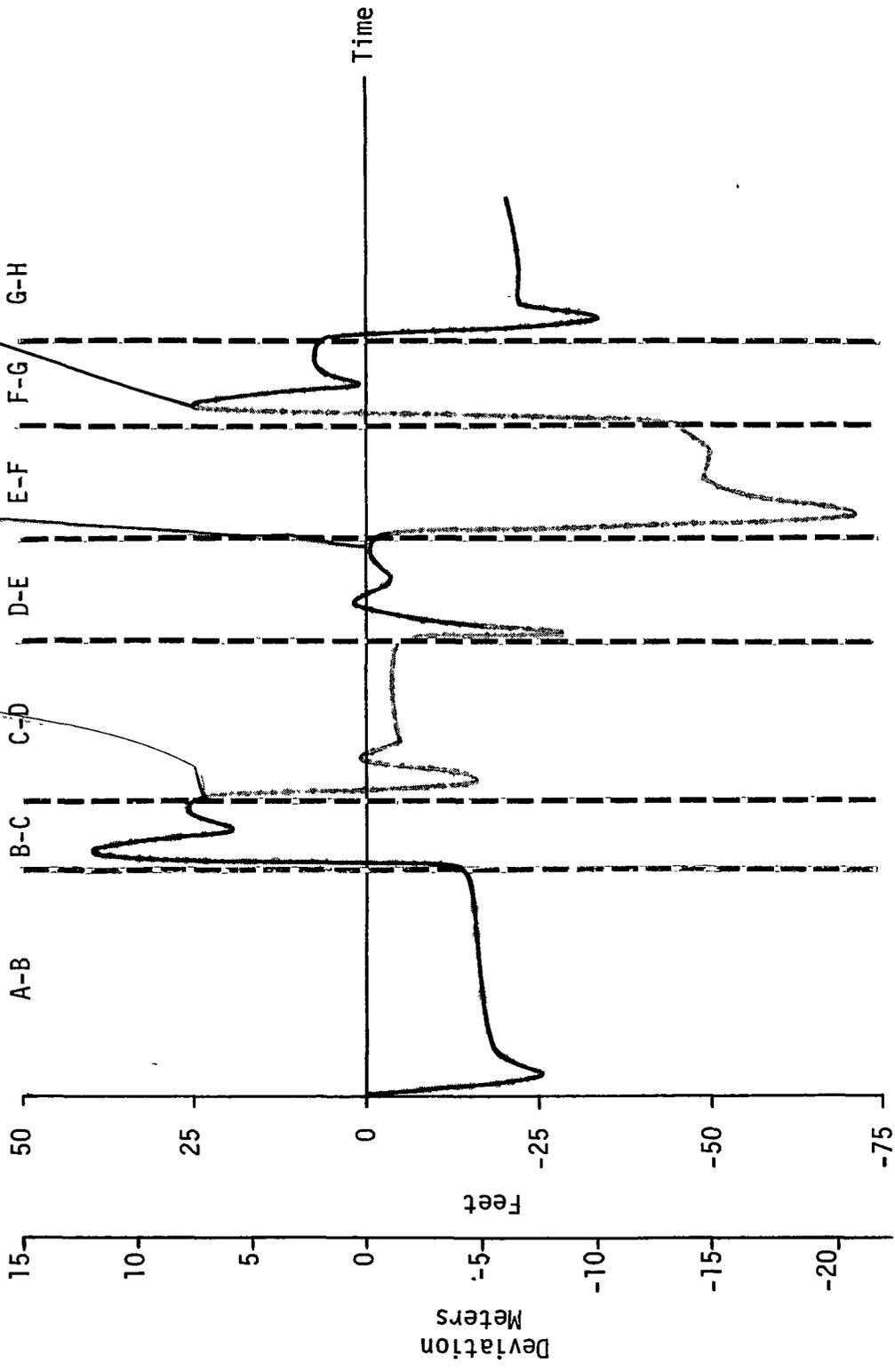


Figure 5.9 DCA Arc Approach - 10.3 M/S (20 kt) Westerly Wind - Continuous Bank Command

this case, the graph of the track deviations is nearly identical to the graph of the wind-free case shown in Figure 5.4. It is doubtful that the relative decrease in the path error realized as a result of this control law modification would warrant the additional system complexity.

Altogether, the previously described simulation exercises indicate that the arc segment approach to Washington National's runway 18 could be executed with the degree of accuracy required to gain a significant noise advantage in concentrating the approach path over the Potomac River where the impact on the population is minimal. Since the width of the river is nominally 370 m (.2 nm), the achieved track must not deviate from the desired track by more than half that distance to realize the noise abatement potential of the curved approach path. Since the deviation observed for all of the preceding simulations never exceeded 46 m (150 ft), these results indicated that the curved approach procedure is possible with current autopilot/guidance system design concepts and also consistent with the measurement errors expected with MLS. These exercises are not in themselves sufficient to conclude that the arc segment approach utilizing MLS is a viable procedure to minimize noise and increase the landing capabilities at Washington National. This conclusion can only be reached after extensive flight testing is conducted with MLS for several representative aircraft types and under various environmental conditions. The logical first step in this direction is to involve the TCV research aircraft in the initial examination of the procedure.

## 5.2 AIRCRAFT PERFORMANCE MODEL VALIDATION

The model validation procedure consisted of exercising several test cases and comparing the results with performance data that was available in the aircraft operations manual. The parameters that were considered for validation were primarily time, distance and fuel to climb or descend. In addition, for the DC-10, rate of climb information was available. Consequently, the rate of climb data for this aircraft was also compared to that of the model. In climb, the speed and thrust profiles that were described in the operations handbook were used to establish a control mode structure which duplicated the conditions under which the data in the handbook were developed. This usually consisted of either constant indicated airspeed or constant Mach number climbs coupled with level altitude acceleration segments. All of the climb cases were validated at maximum continuous thrust. During the validation of the cruise segments a level altitude throttled cruise control mode structure was established to duplicate the data that was available in the handbook. For the cruise cases, once the speed, altitude and weight conditions had been met, the only parameter that was used for evaluation was specific range. During descents the control mode structure was again set up to duplicate the conditions that were described in the handbooks for the standard descents. These cases generally consisted of level altitude deceleration segments followed by constant indicated airspeed or constant Mach number descent with the thrust set in the flight idle position. The parameters that were recorded included time to descend, distance to descend and fuel to descend. The following paragraphs describe in some detail the results of the validation phase of the project.

### 5.2.1 B737-200 Validation

The handbook climb cases for the B737 consisted of two sets of tables of altitude vs weight. For each altitude and weight combination, the accumulated

time, distance, fuel and speed were shown. One set of data was provided for the high speed climb procedure and a second set consisted of the long range climb procedure. Three different weights of aircraft were considered in the validation runs. The first weight selected was that of an aircraft near its full gross maximum weight of 52,163 Kg (115,000 lbs) at brake release. The second case considered was that of a medium weight aircraft typical of many aircraft used in short and medium haul traffic situations. The weight of this aircraft at brake release was 40,823 Kg (90,000 lbs). The third case was a lightly loaded aircraft whose brake release weight was 29,483 Kg (65,000 lbs). Cruise validation runs were begun at 1828 m (6000 ft) using the initial conditions indicated in the handbook data. Since speeds were shown at each of the weight/altitude combinations in the handbook data, these speeds were incorporated into the control mode structure and a delta Mach/delta altitude climb is assumed to occur between the selected altitude levels. The simulation exercise was terminated when the aircraft reached FL350. The results of the validation runs for the high speed climb are displayed in Figures 5.10, 5.11 and 5.12. It can be noted that the distance and fuel to climb curves overlay the handbook climb curves almost exactly while the time to climb curve showed some bias as the aircraft reached the higher altitudes. This indicated that the model was taking longer to climb than indicated in the performance handbook. On an incremental basis from altitude level to altitude level, the variations are not great. However, when accumulated over the entire run the errors at the higher altitudes appear to be significant. Several adjustments to aircraft thrust and drag were made in an attempt to reduce this bias in the time to climb data. However, no combination of thrust or drag change could improve the time to climb curve without adversely affecting the distance to climb curve. However, a differential type of climb analysis was anticipated in which a base line is

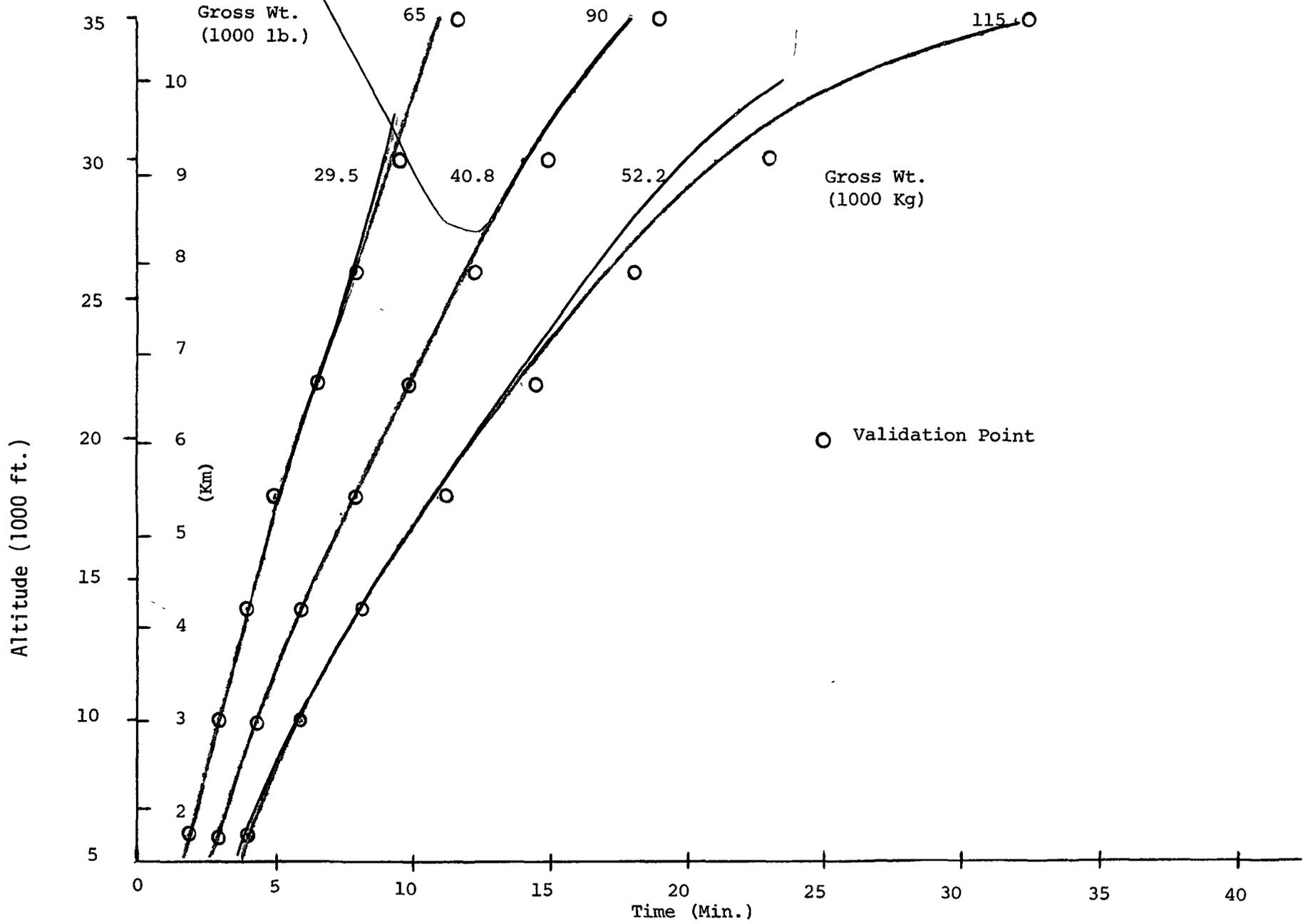


Figure 5.10 B737 Time to Climb - High Speed Climb

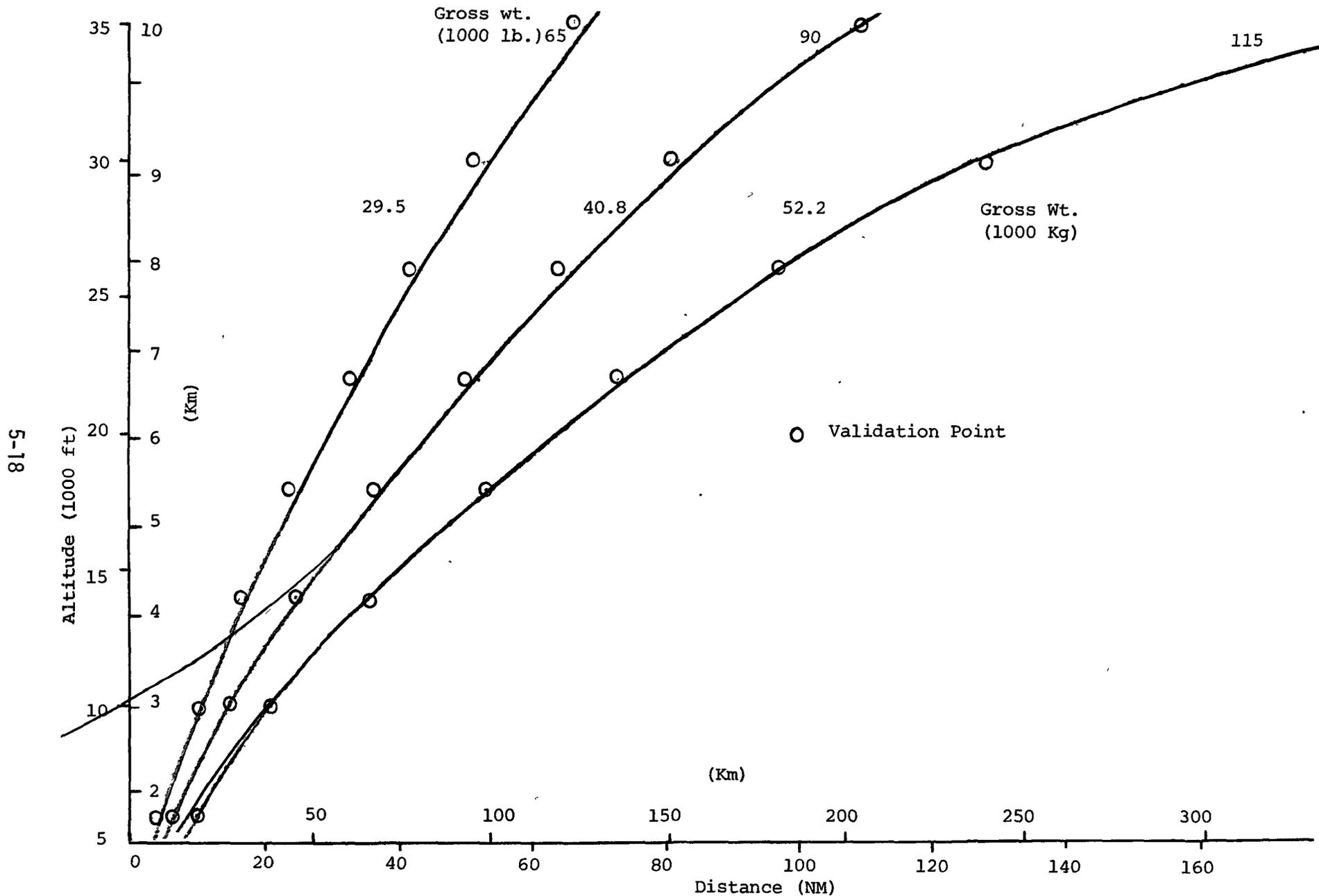


Figure 5.11

B737 Distance to Climb - High Speed Climb

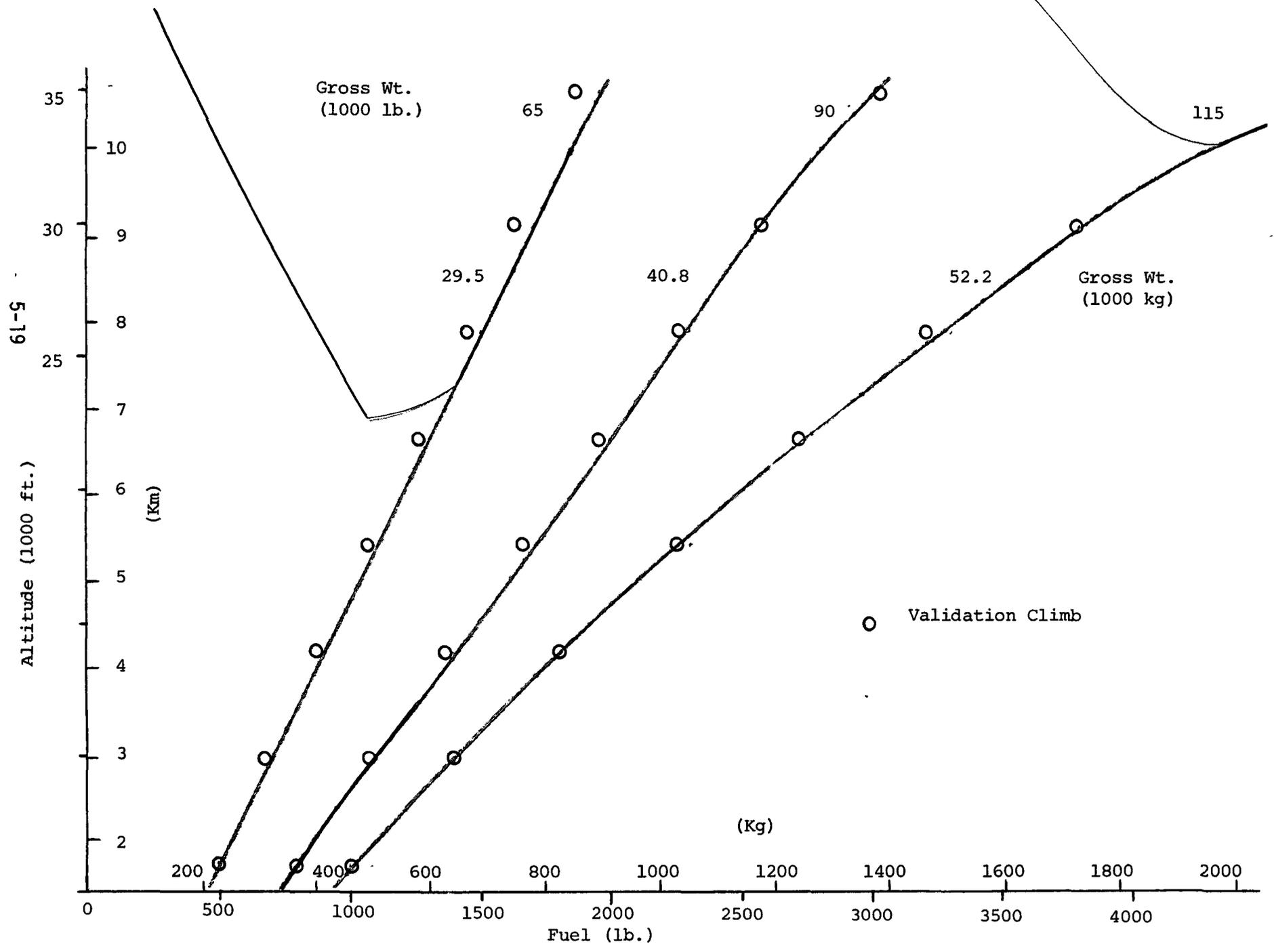


Figure 5.12 B737 Fuel to Climb - High Speed Climb

selected and all other results are compared with respect to this base line. Thus biases in the data would tend to be cancelled by this analysis technique. In this light, the bias in the time to climb data was not considered significant and no further efforts to remove or account for this bias were undertaken.

The long range climb data for the B737 climb is shown in Figures 5.13, 5.14 and 5.15. The same bias that was apparent in the high speed climb cases was observed in the long range climb data as well. However, since the same analysis procedure was applied to the long range data, the bias was not considered important in the final analysis.

The cruise validation consisted of exercising the model at several altitude, weight, and speed combinations and comparing the resulting specific range values that were achieved in the model runs to those contained in the performance handbook. The same three weight combinations that were used in climb were used in the cruise validation. The altitude levels selected for validation ranged from 1829 m (6000 ft) to 7925 m (26,000 ft) in 1219 m (4000 ft) increments. The comparisons for each of the validation runs and the related performance data from the aircraft's operational handbook are shown in the Figures 5.16 through 5.21. It can be seen that the agreement between the validation runs and the handbook data is quite acceptable at most of the points checked. Slight discrepancies were noted at the lower altitudes, particularly the 1219 m (6000 ft) case; however, they were not considered significant enough to affect the validity of the subsequent cruise analysis.

Two weights and two types of descent procedures were considered in the B737 descent validation task. The descent cases were described both by the speed and approximate rate of descent schedules in the performance handbook. No weight variation was specified for either type of speed schedule, i.e., long range descent or high speed descent. However, two weights were selected in the performance model cases for each of the performance profiles. The weights selected

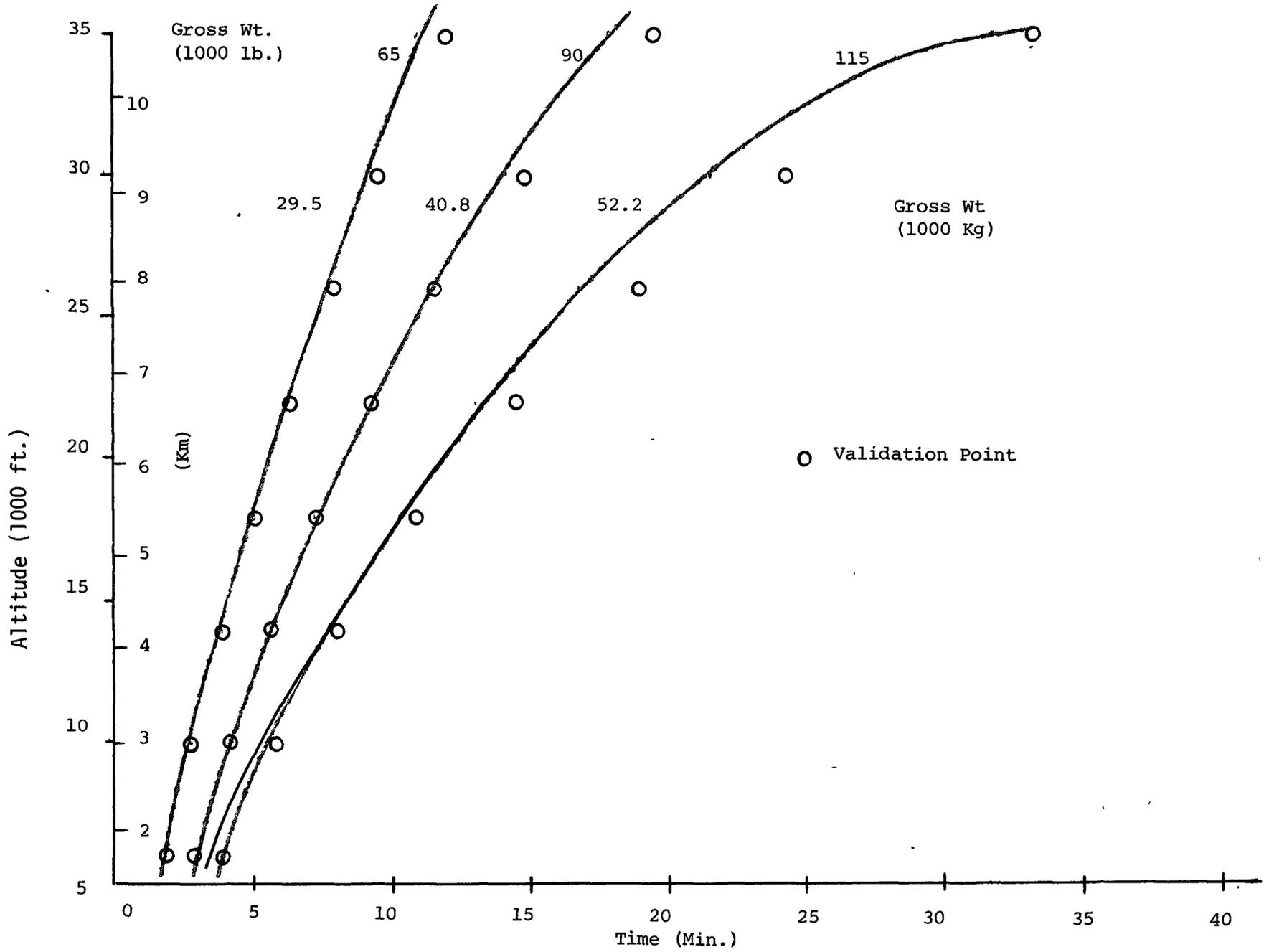


Figure 5.13 B737 Time to Climb - Long Range Climb

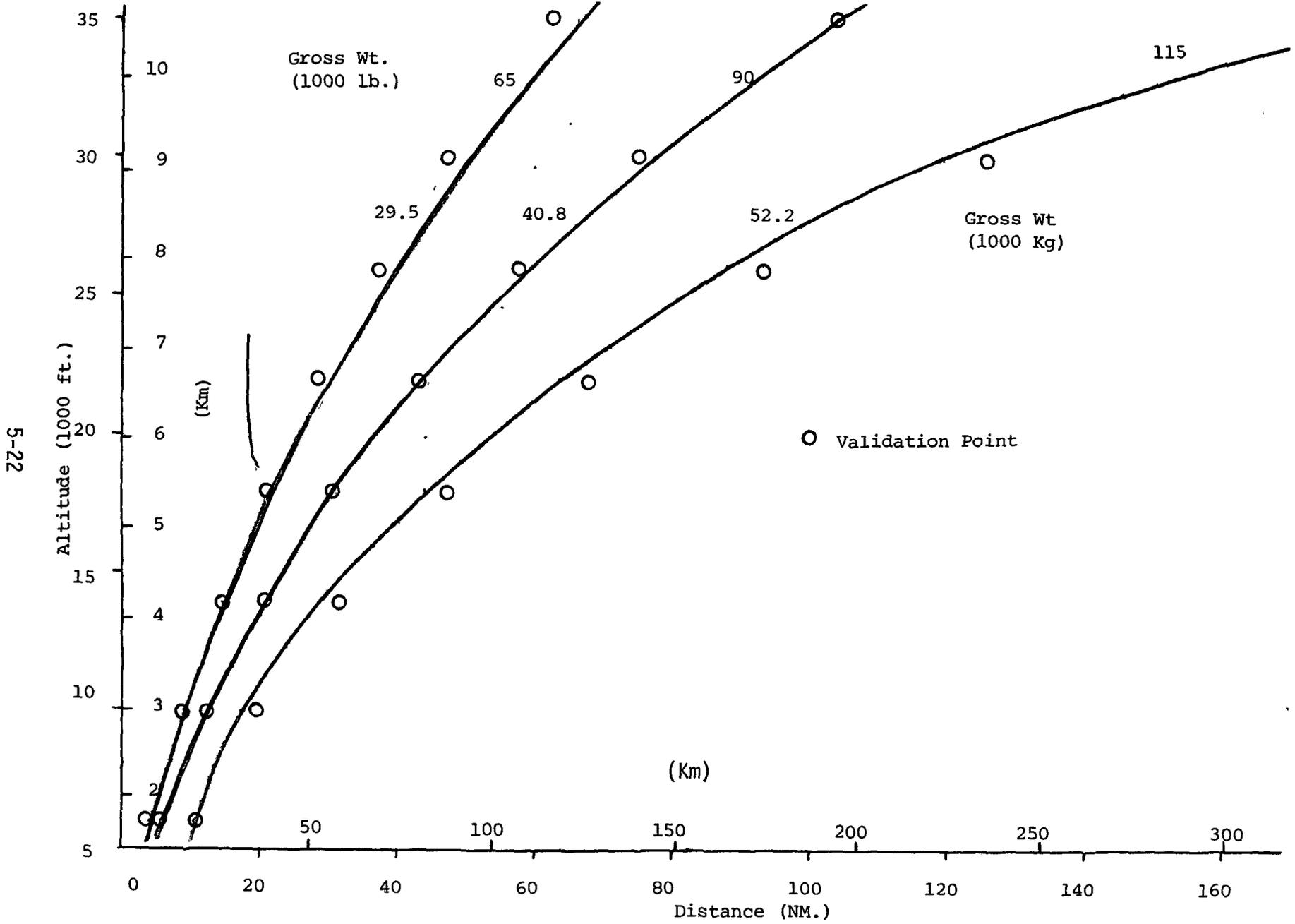


Figure 5.14

B737 Distance to Climb - Long Range Climb

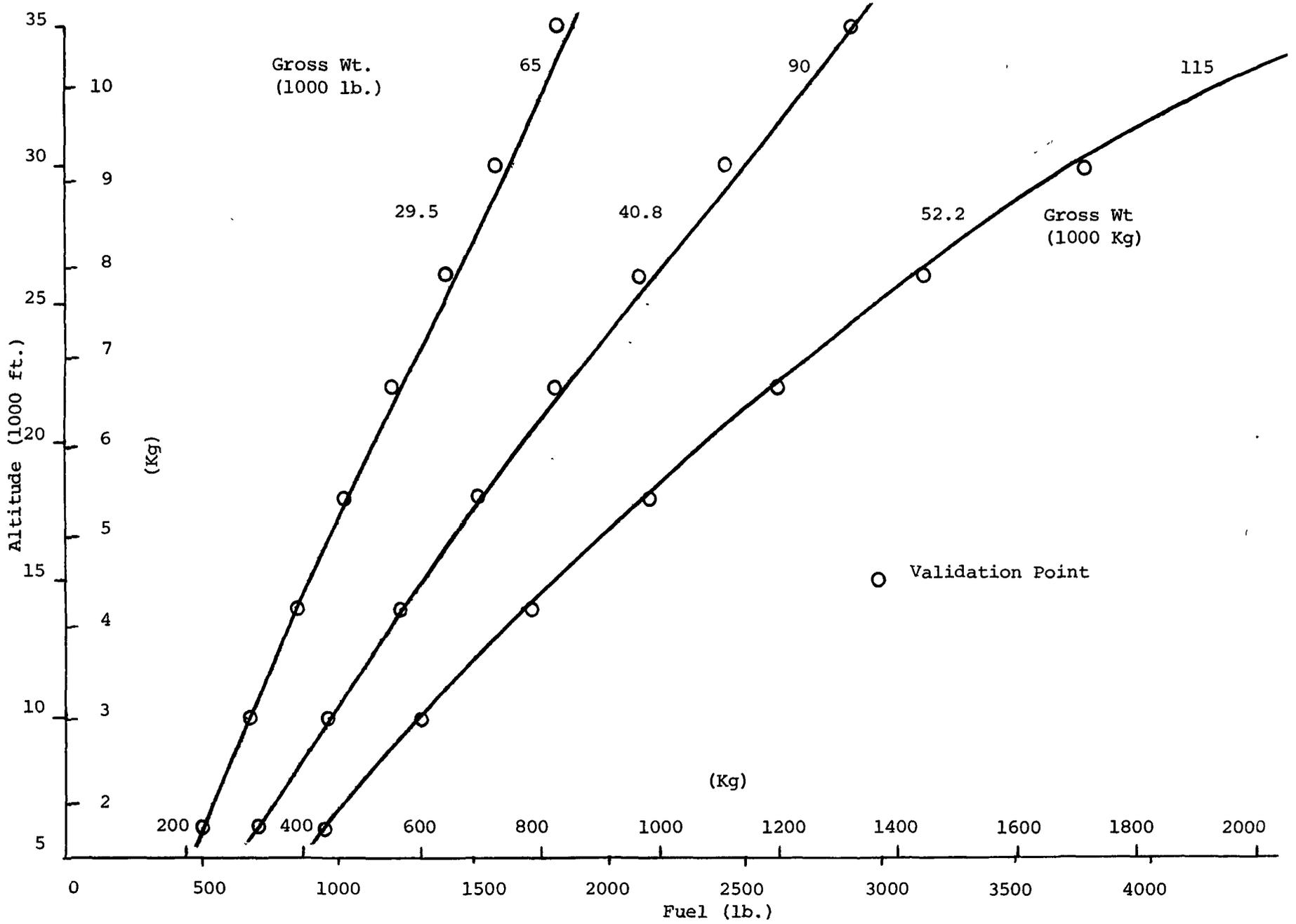


Figure 5.15

B737 Fuel to Climb - Long Range Climb

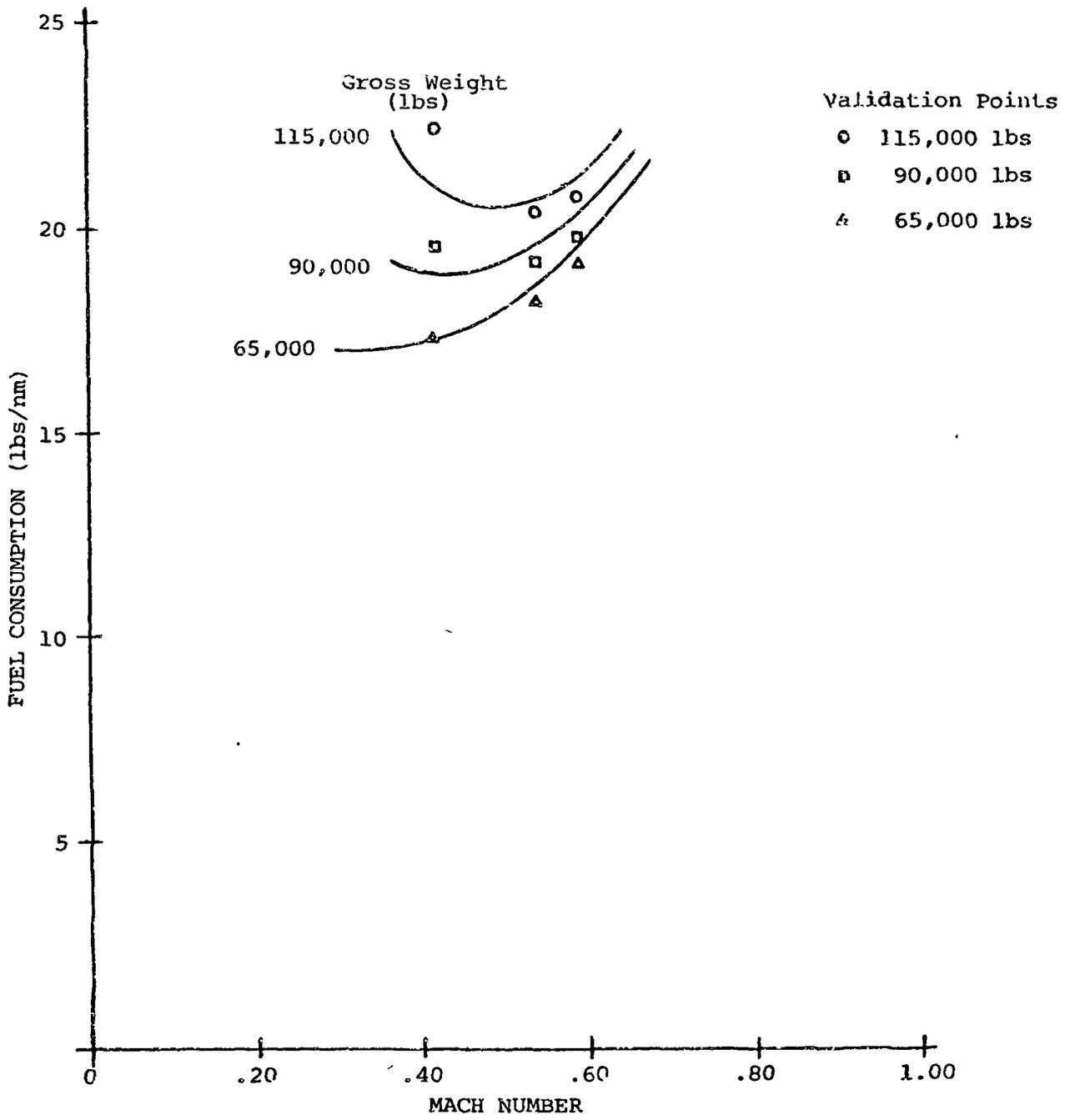


Figure 5.16 B737 Cruise Validation - 6,000 ft

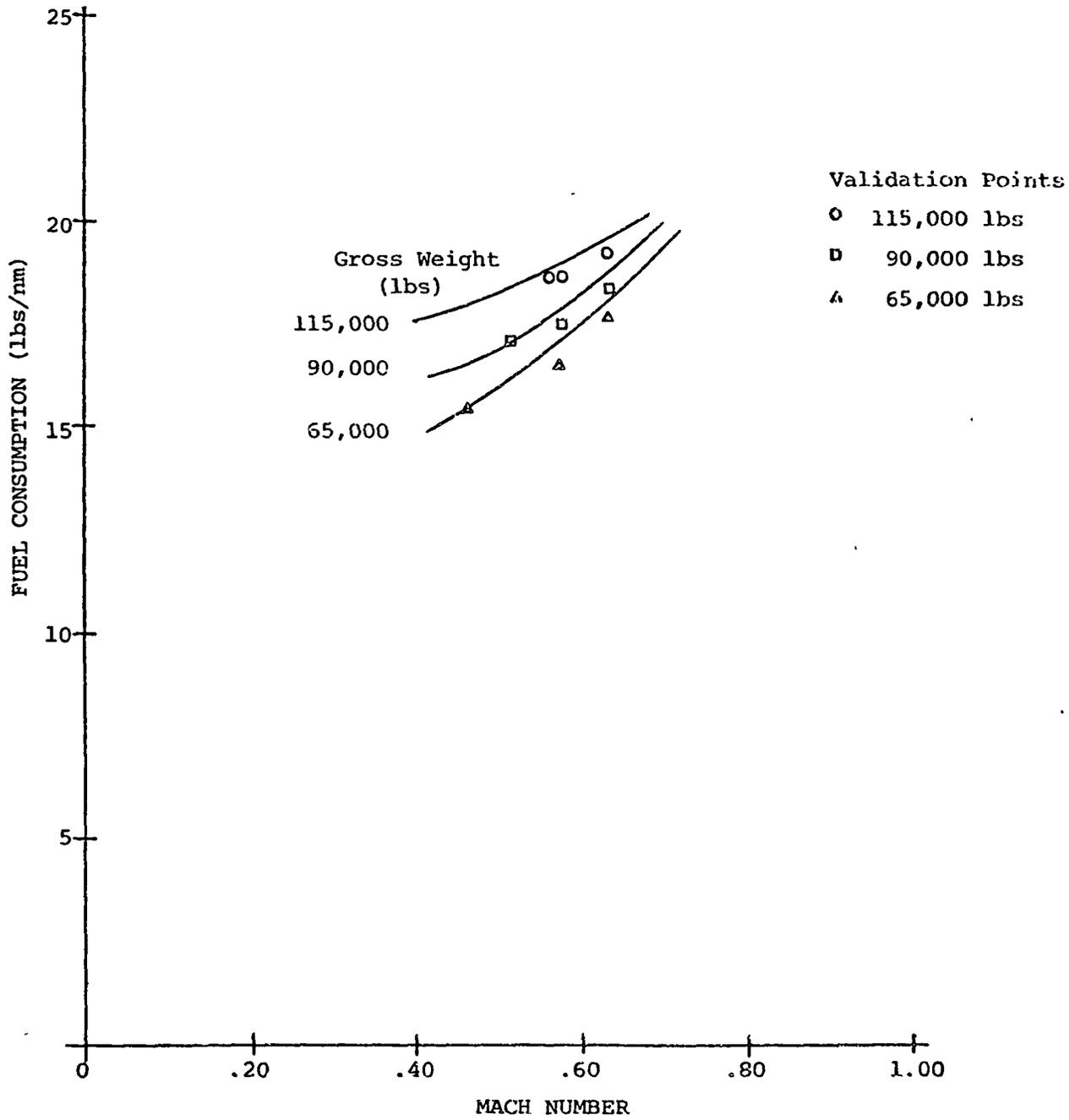


Figure 5.17 B737 Cruise Validation - 10,000 ft

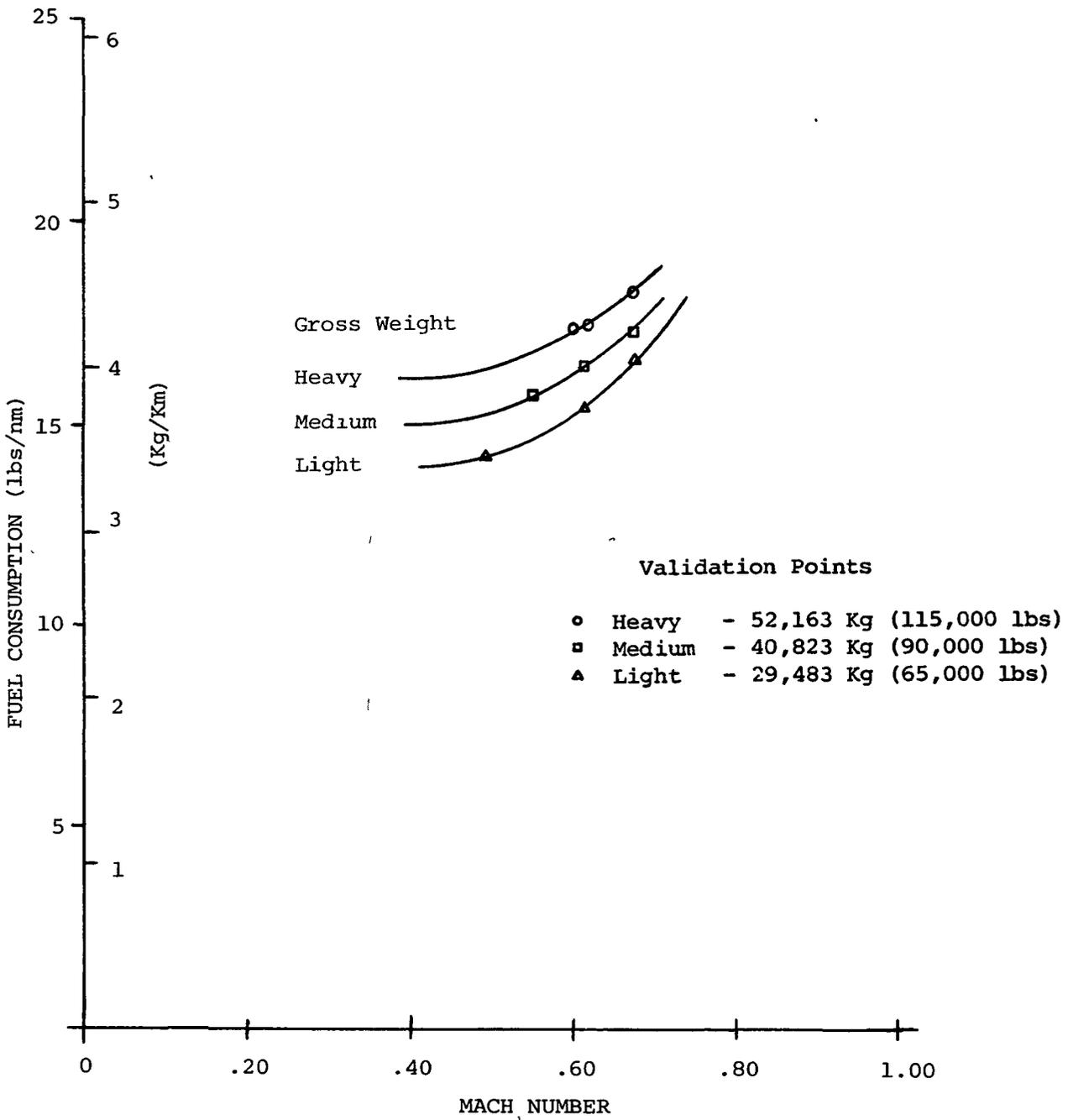


Figure 5.18 B737 Cruise Validation - 4269 m (14,000 ft)

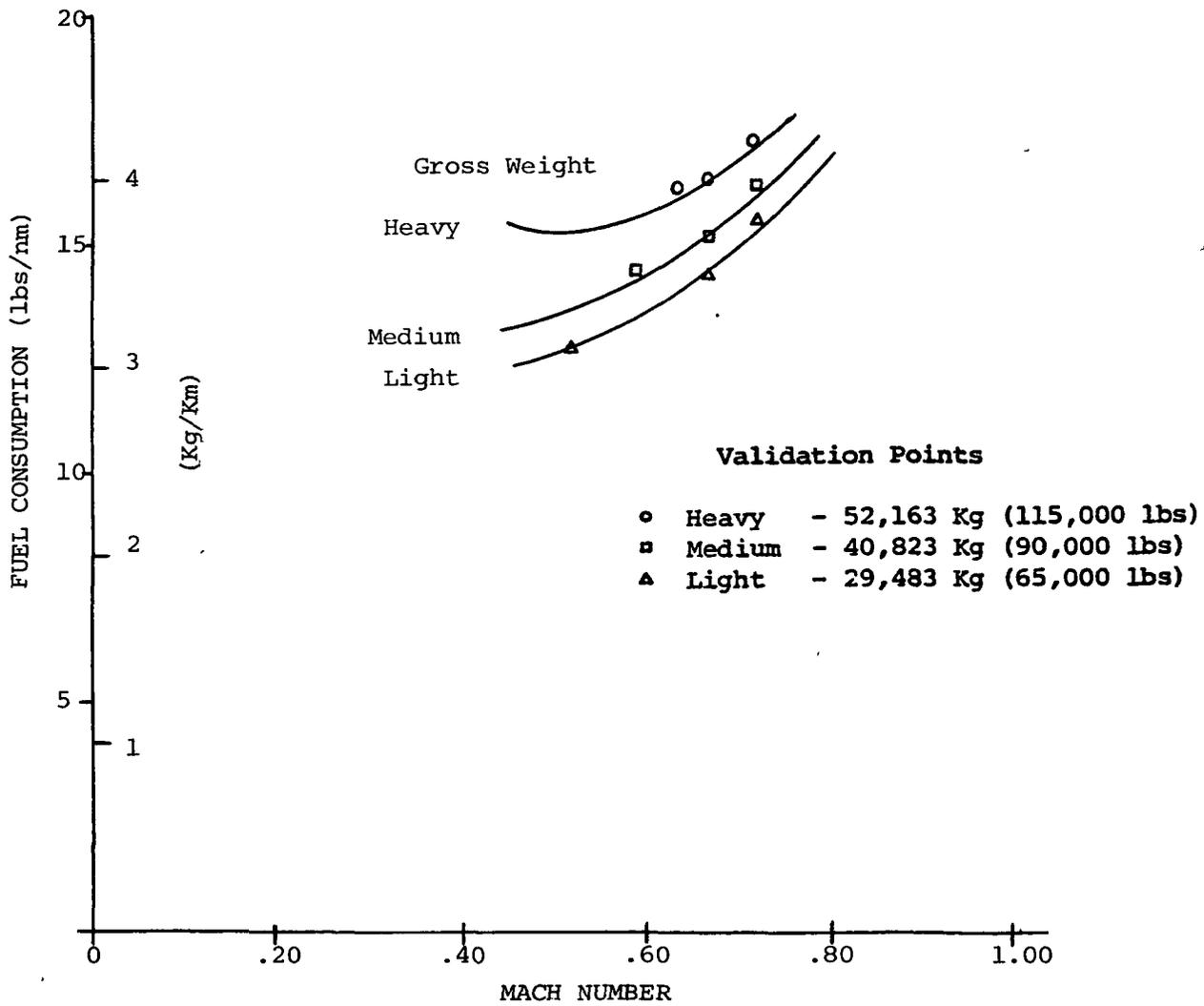


Figure 5.19 B737 Cruise Validation - 5046 m (18,000 ft)

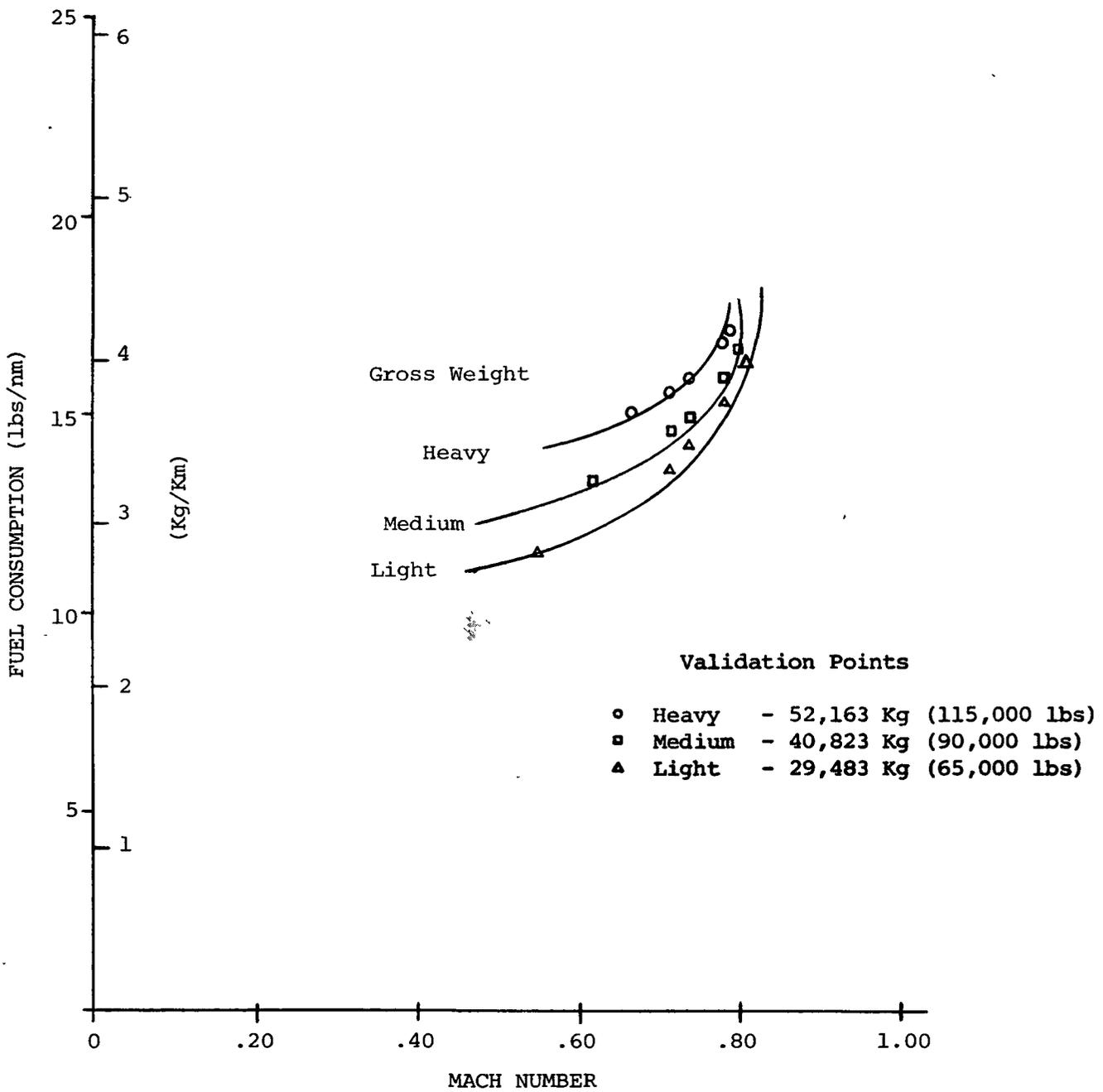


Figure 5.20 B737 Cruise Validation - 6706 m (22,000 ft)

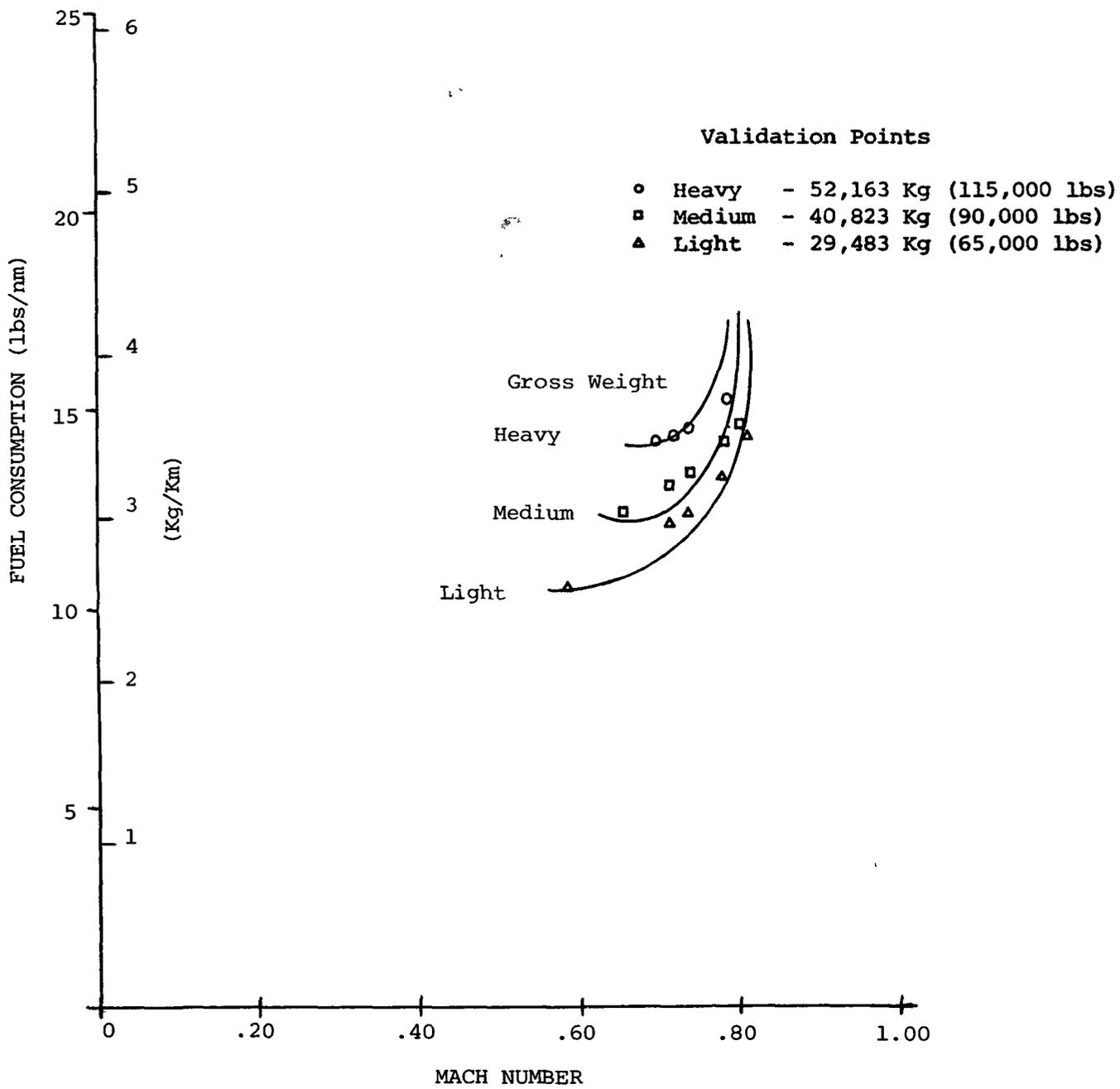


Figure 5.21

B737 Cruise Validation - 7925 m (26,000 ft)

were 40,823 Kg (90,000 lbs) and 29,483 Kg (65,000 lbs). The results of the B737 descent validation in a high speed descent are shown in Figures 5.22, 5.23 and 5.24. Large discrepancies were noted in the time and distance profiles.

Examining the handbook data, it was apparent that events such as the deceleration at 3048 m (10,000 ft) to 129 m/s (250 kts) had not been considered. Rather, it is believed that approximate techniques were used in preparing the handbook data and as a result, large discrepancies in the data can be expected. The overall time, distance and fuel required to descend are in general agreement with the handbook data while individual data points can be in error. This same phenomenon is seen in the long range descent data shown in Figures 5.25, 5.26 and 5.27. Again the overall descent results are close to the handbook values but individual data points vary substantially from the handbook values.

The same reasoning concerning differential analysis techniques discussed previously applies to the descent phase of flight as well. Consequently, due to the inexactness of the handbook data for the B737, no further attempt was made to reconcile the performance model data with the handbook data.

#### 5.2.2 DC 10-Series 10 Validation

The source of performance data for the DC-10-10 was more detailed and complete than that for the B737. Consequently, the DC-10 profiles could be validated to a greater degree of accuracy than the B737 profiles. In the climb cases, an additional set of rate of climb curves was available for this aircraft as well. This enabled the checking of rate data as well as position data which proved to be invaluable in obtaining a valid aircraft thrust and drag model.

The climb validation cases for the DC-10 were chosen according to aircraft weight and speed profiles. Three weights, 108,862 Kg (240,000 lbs), 163,293 Kg (360,000 lbs) and 201,395 Kg (440,000 lbs) were selected for analysis. These weights span the range shown in the handbook. Both a high speed and

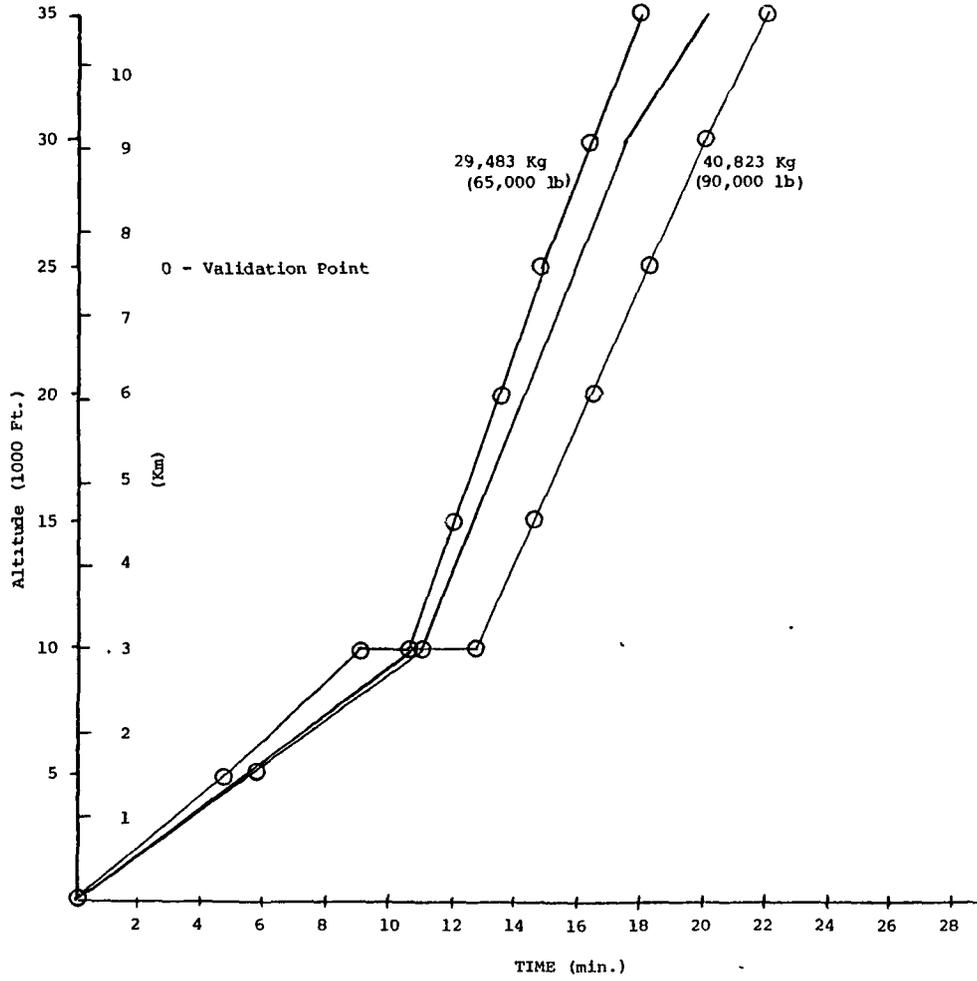


Figure 5.22 B737 Descent Validation, High Speed Descent, Time

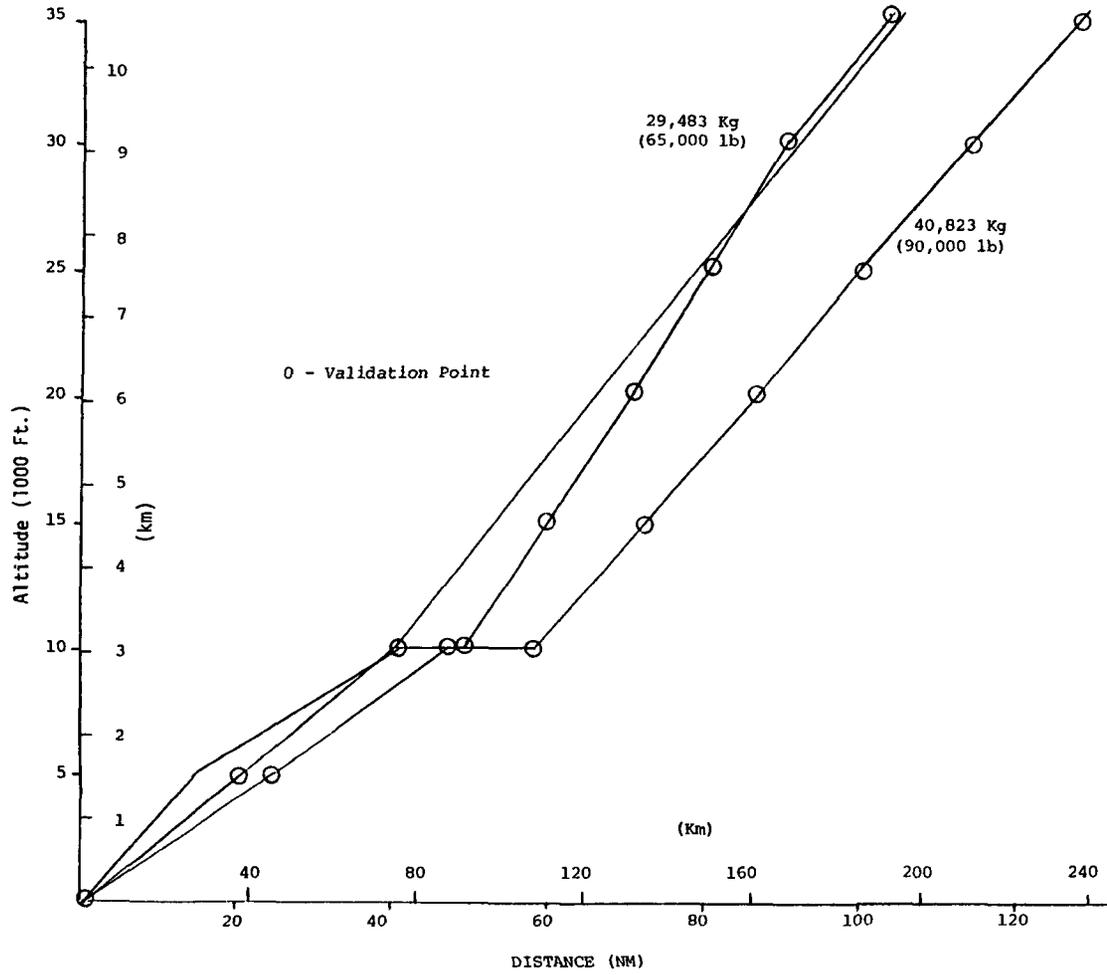


Figure 5.23 B737 Descent Validation, High Speed Descent, Distance

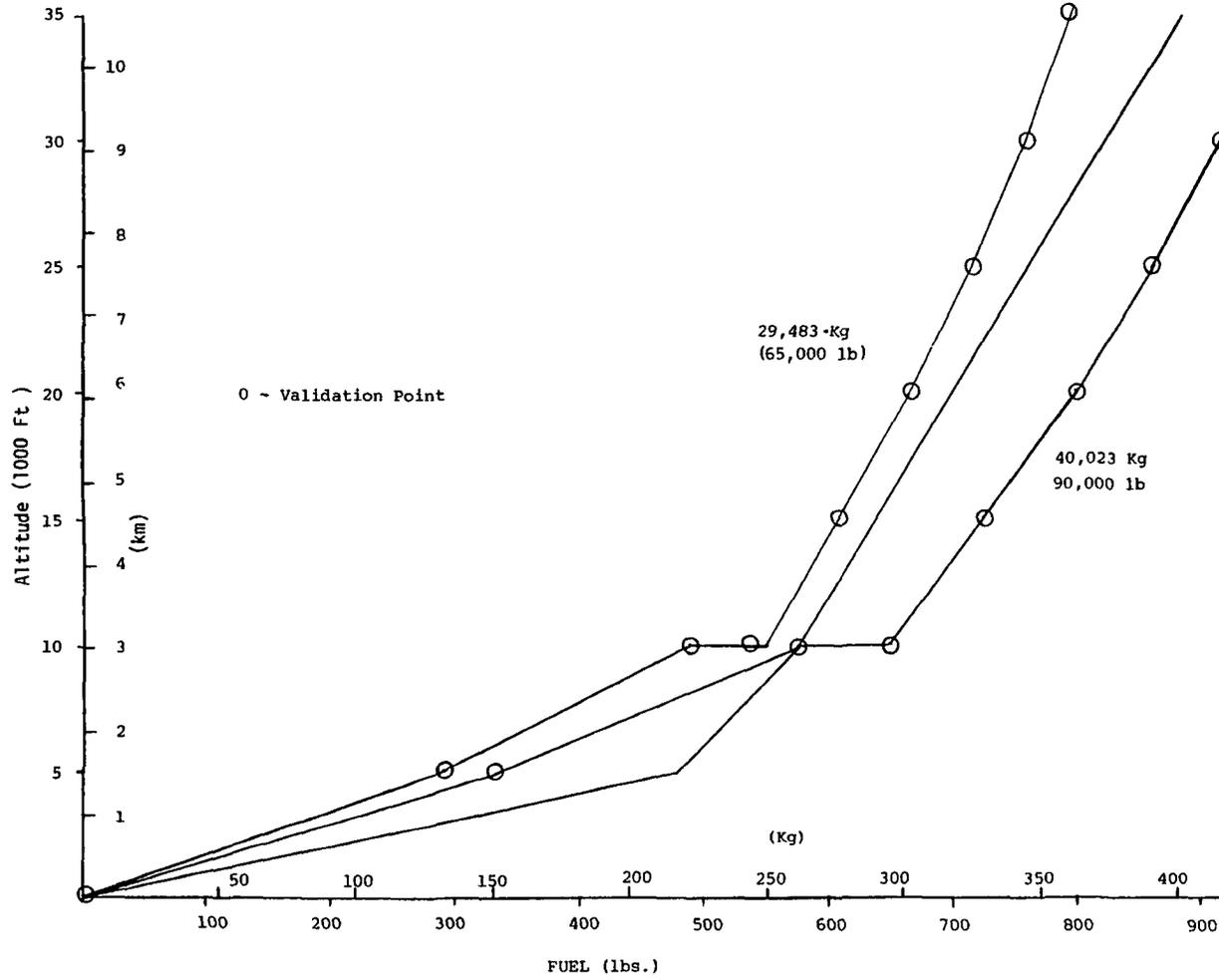


Figure 5.24 B737 Descent Validation, High Speed Descent, Fuel

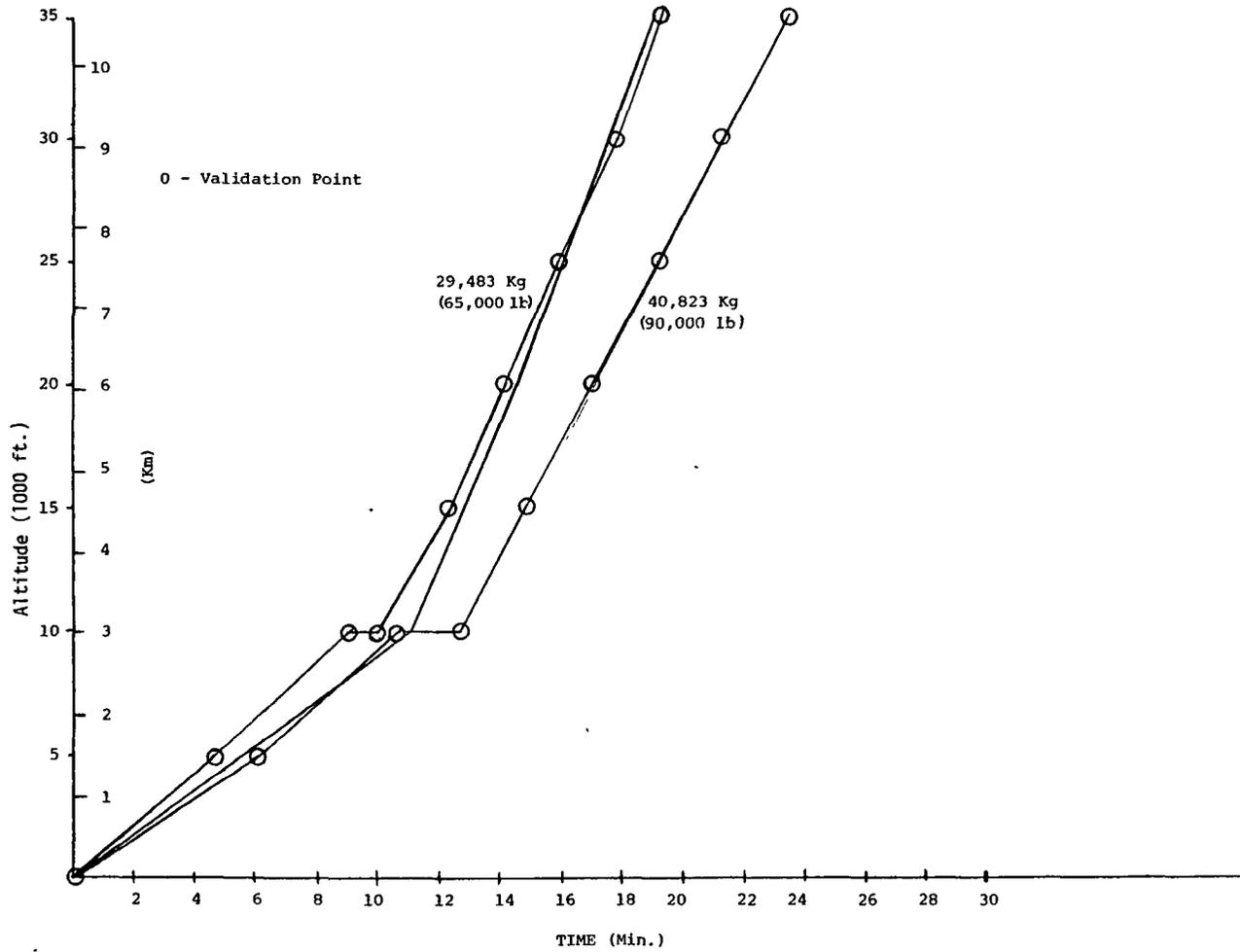


Figure 5.25 B737 Descent Validation, Long Range Descent, Time

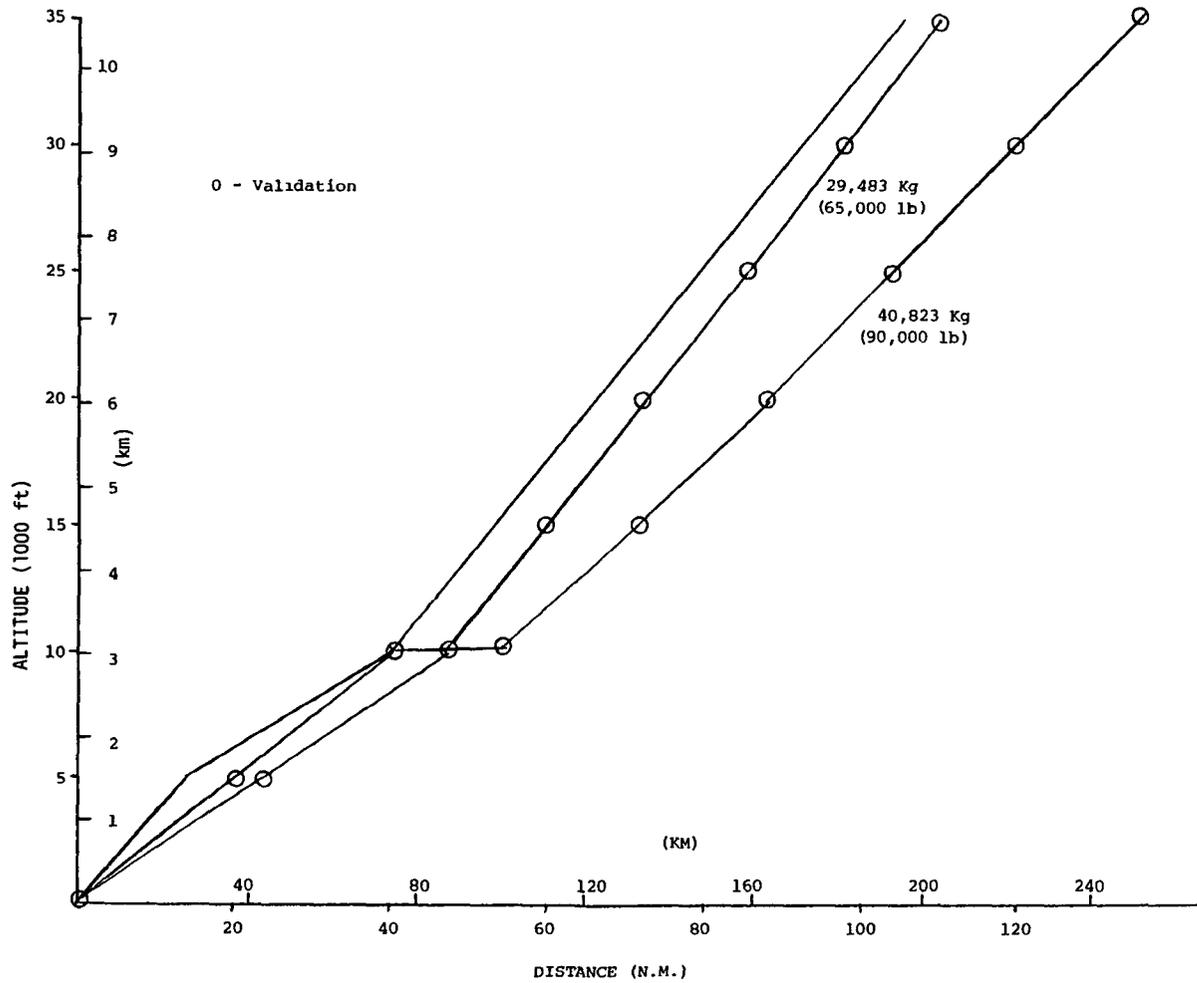


Figure 5.26 B737 Descent Validation, Long Range Descent, Distance

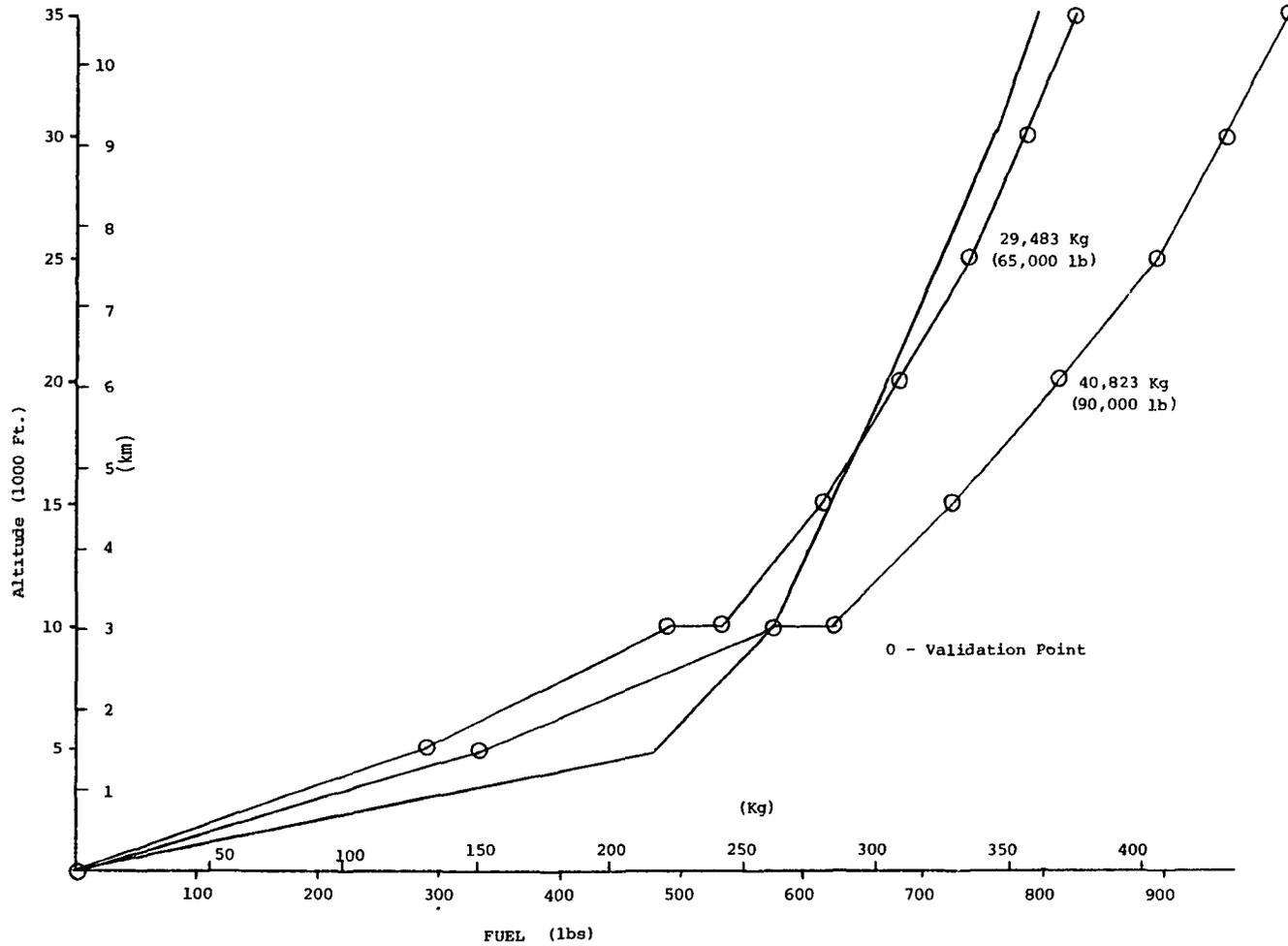


Figure 5.27 B737 Descent Validation, Long Range Descent, Fuel

a long range climb are shown in the handbook. The high speed climb consists of a constant IAS climb at 129 m/s (250 kt) to 3048 m (10,000 ft), a level acceleration to 175 m/s (340 kt), a constant IAS climb to a Mach number of .85 and climb at constant Mach number until the desired cruise altitude is reached. The cruise altitude was chosen to be FL350 in the validation cases. The comparison of the high speed climb from the performance model and the handbook data is shown in Figures 5.28, 5.29, 5.30 and 5.31. It can be seen that generally excellent agreement between the model and the handbook was obtained for the time, distance and fuel data. The rate of climb data indicates that the model has a slightly greater rate of climb capability than indicated by the aircraft handbook. The differences are slight however, and should produce no significant error in the data obtained from the model.

The validation data that was obtained for the long range climb is shown in Figures 5.32, 5.33, 5.34 and 5.35. The long range climb procedure consists of a constant IAS climb from sea level to 3048 m (10,000 ft) at 129 m/s (250 kt), a level altitude acceleration to 154 m/s (300 kt), a constant IAS climb to a Mach number of .82 followed by a constant Mach climb to cruise altitude. The model data is in substantial agreement with the handbook data for all phases of the DC-10 climb. Again, as with the high speed climb, a slightly greater rate of climb is shown by the model than in the handbook. However, no significant differences can be observed in the time, distance and fuel to climb curves. Consequently, the model will produce accurate time, distance and fuel to climb data.

The validation of the DC-10 cruise model consisted of measuring the fuel consumed by the model aircraft at three different weights, four different altitudes and three different speed values. The weights that were chosen were the same as those selected for the DC-10 climb cases. The altitudes selected for analysis

0 - Validation Point

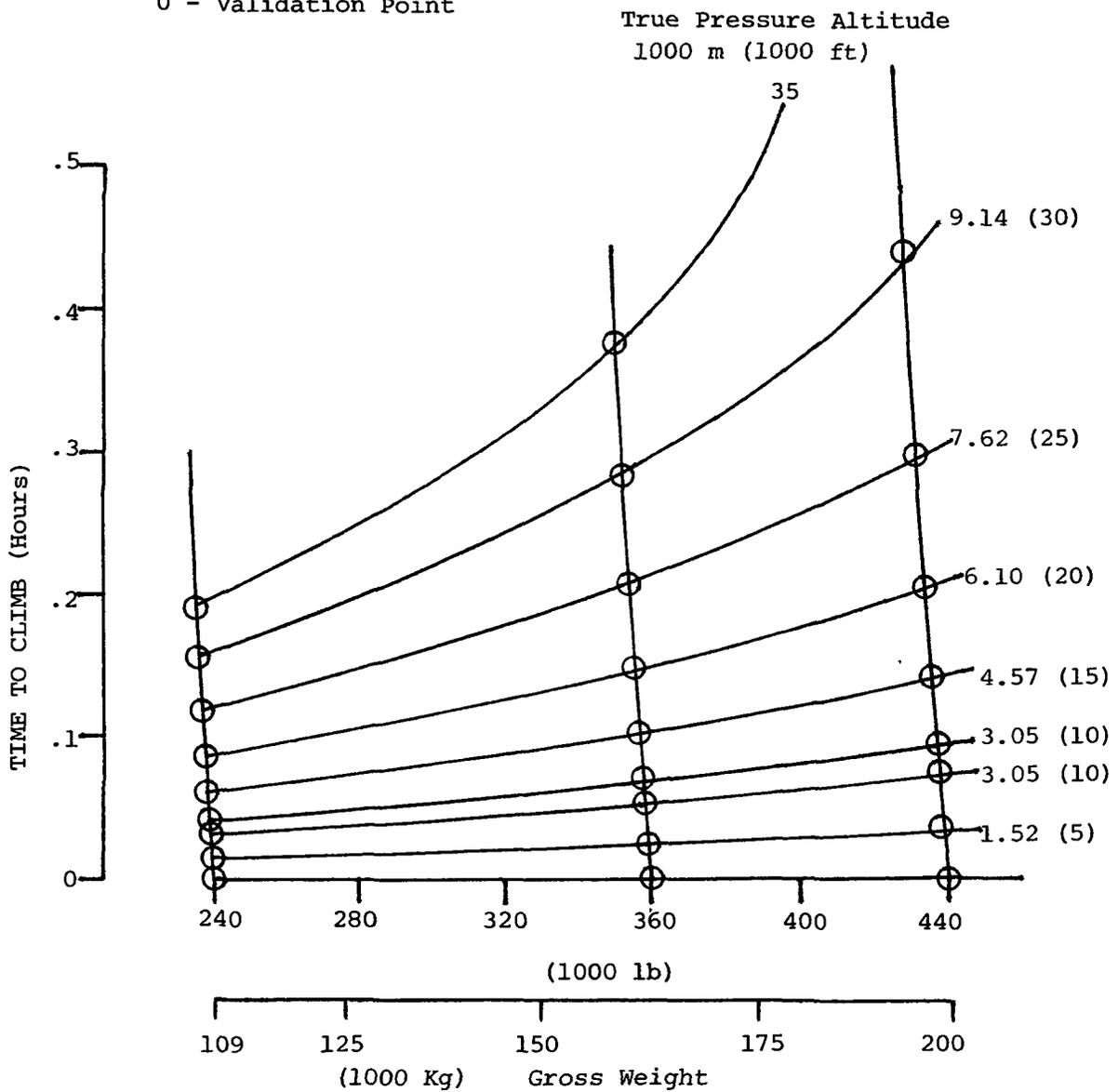


Figure 5.28

DC-10 Time to Climb - High Speed Climb

o - Validation Point

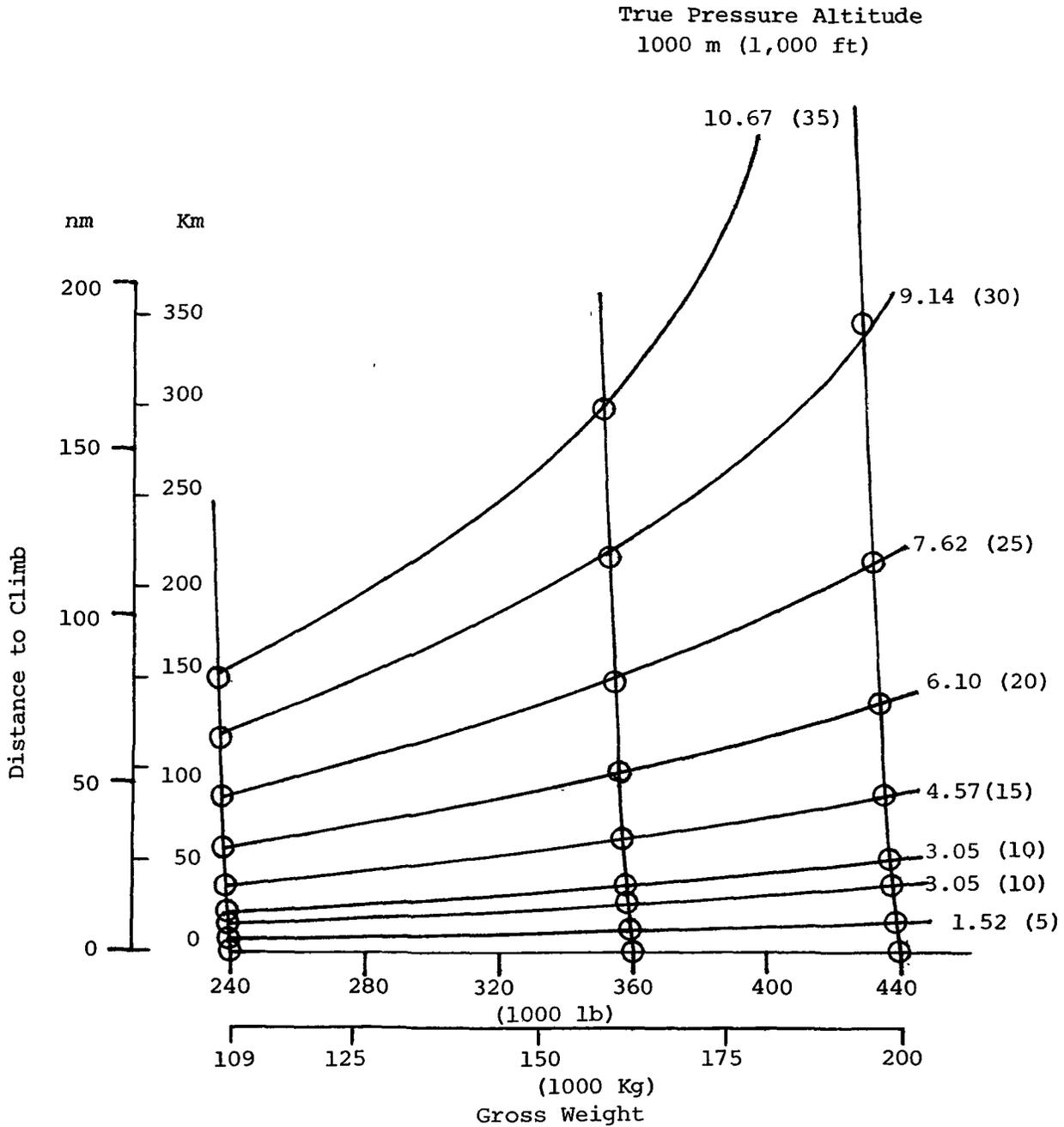


Figure 5.29 DC-10 Distance to Climb - High Speed Climb

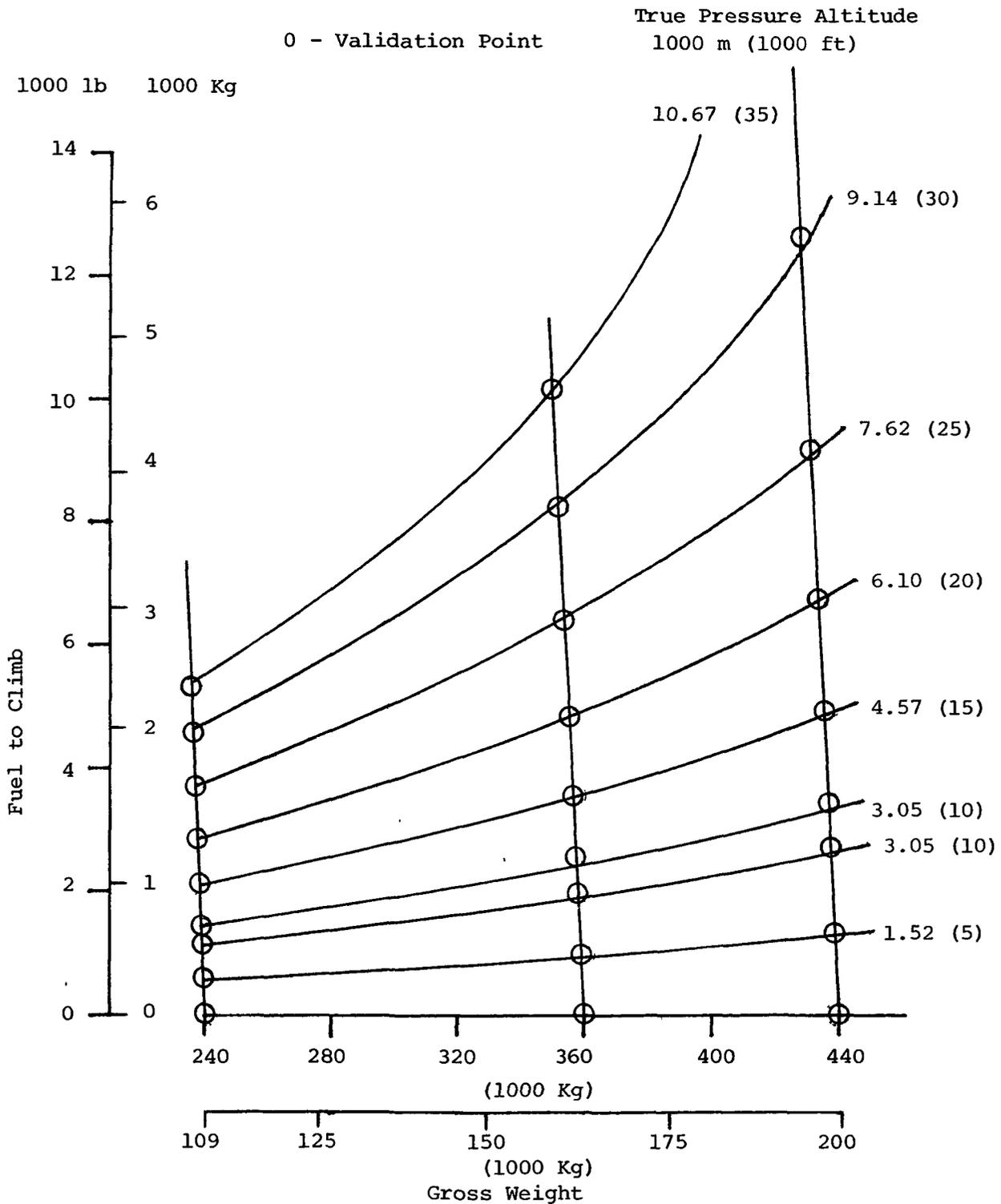


Figure 5.30 DC-10 Fuel to Climb - High Speed Climb

0 - Validation Point

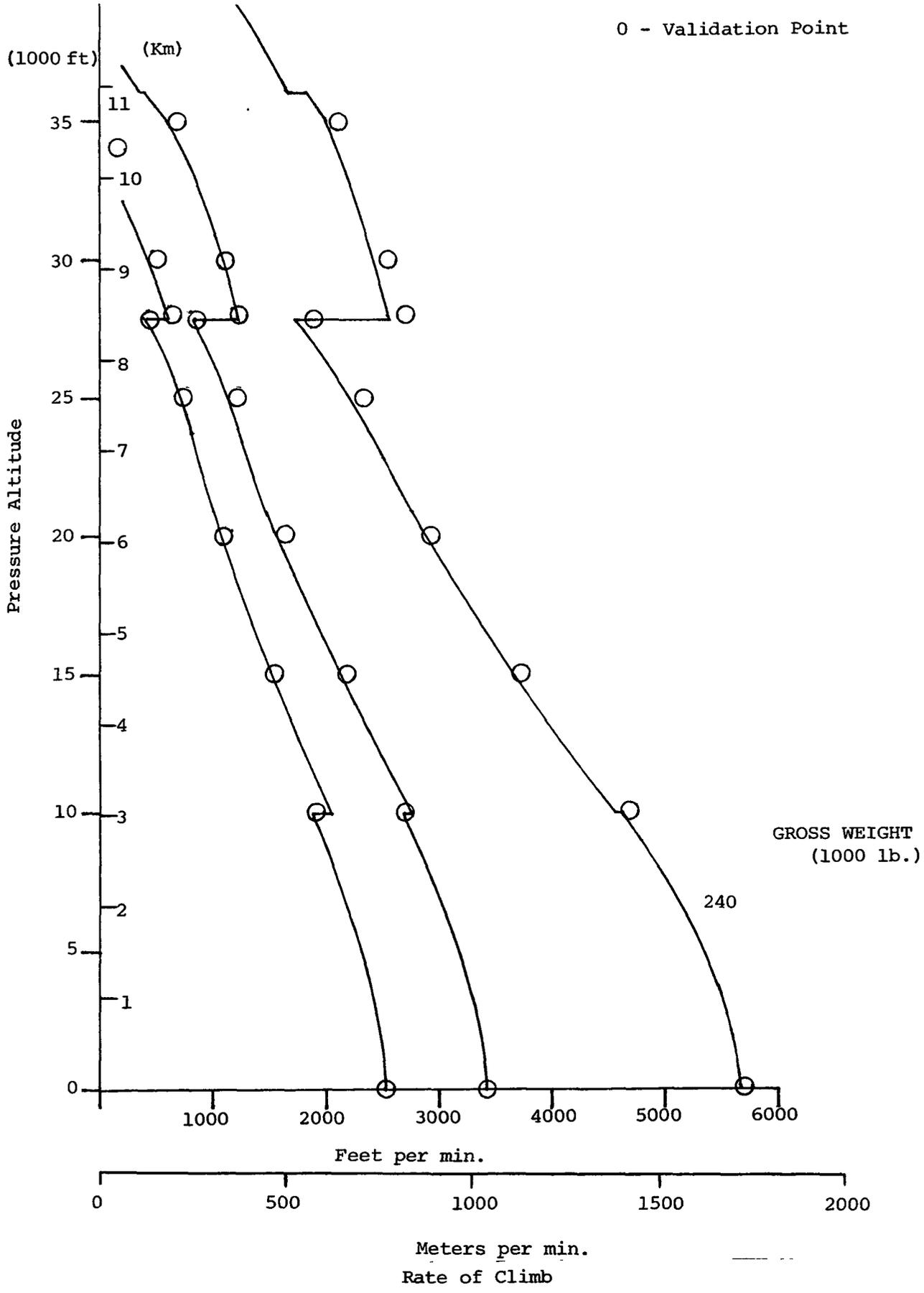


Figure 5.31 DC 10 Rate of Climb - High Speed Climb

0 - Validation Point

True Pressure Altitude  
1000 m (1000 ft)

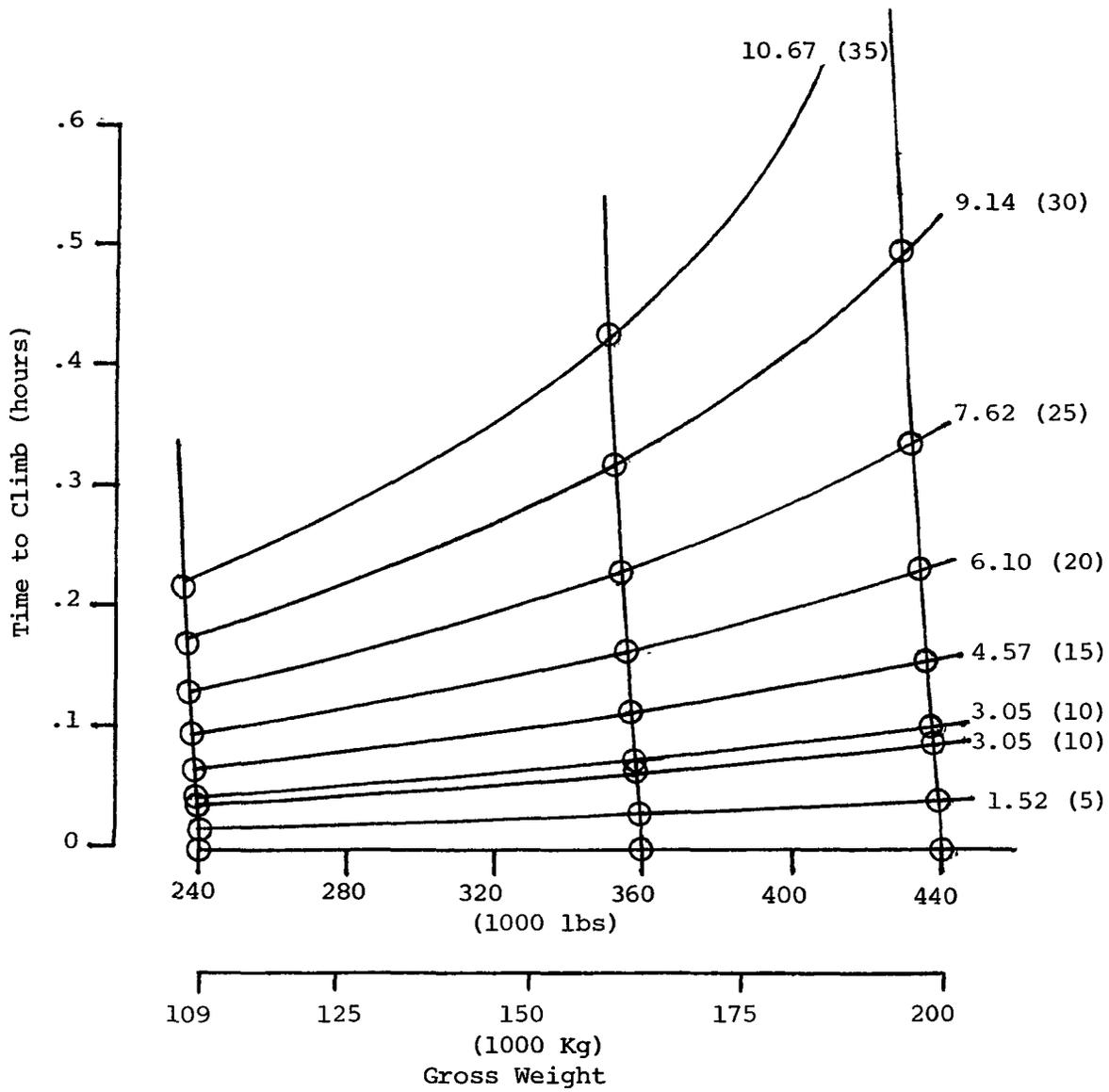


Figure 5.32 DC-10 Time to Climb - Long Range Climb



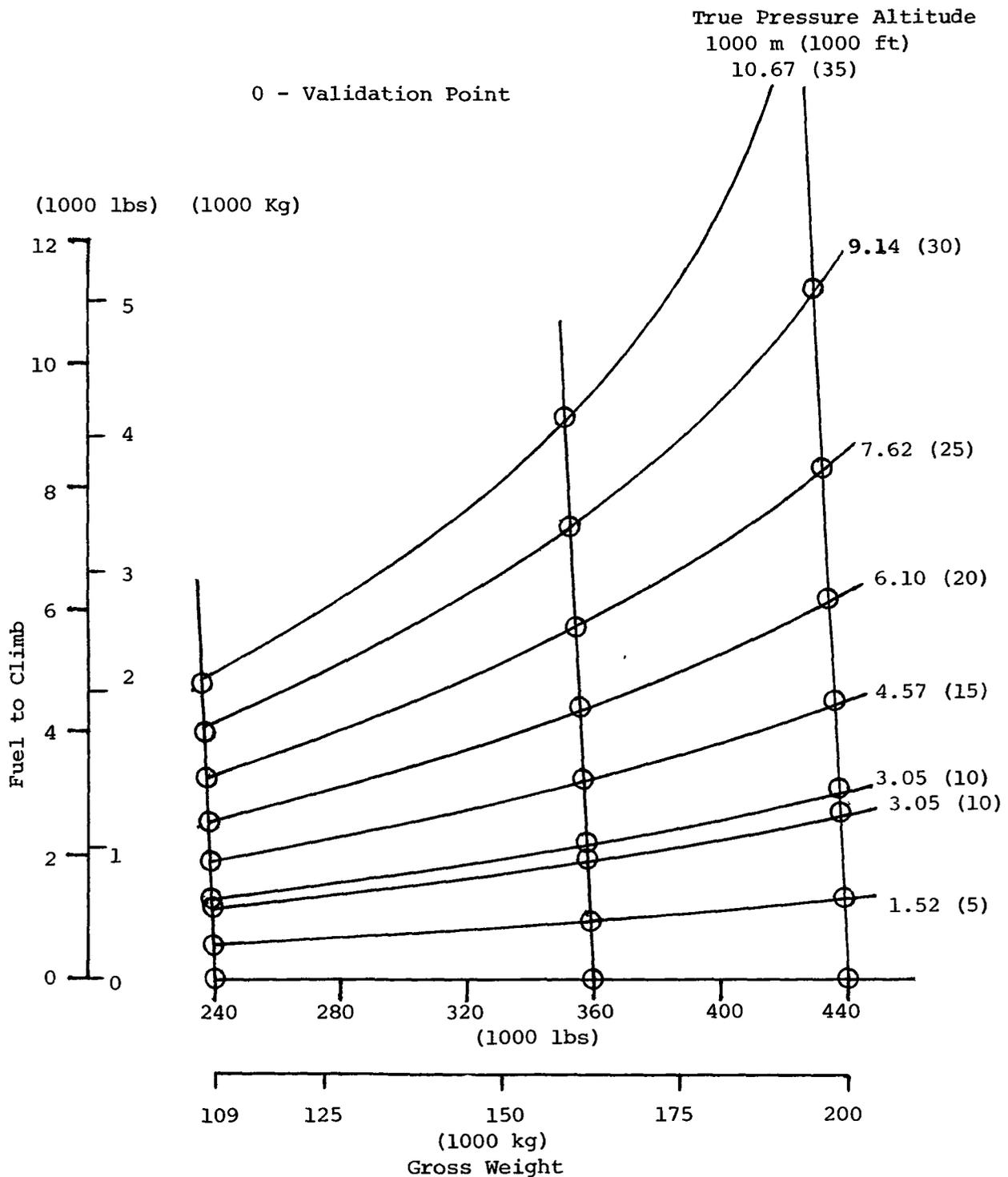


Figure 5.34 DC-10 Fuel to Climb - Long Range Climb

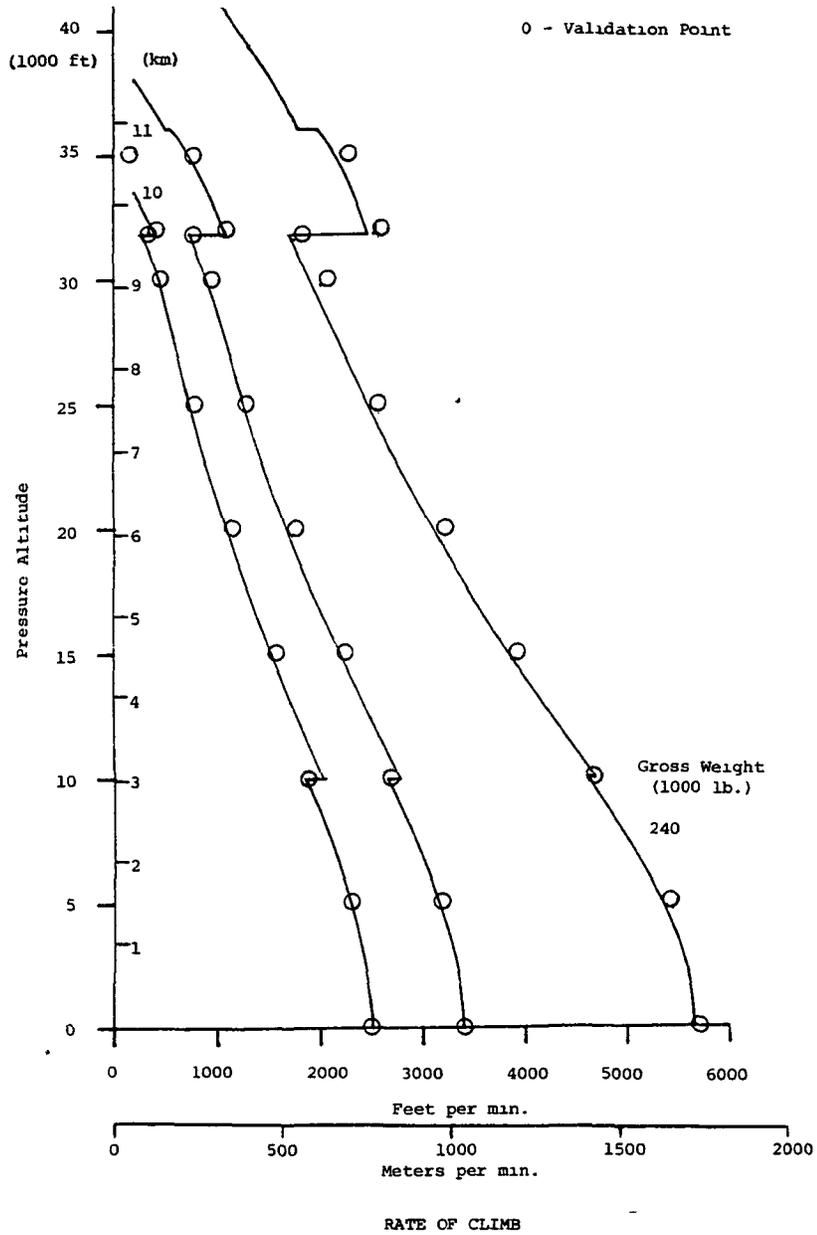


Figure 5.35 DC-10 Rate of Climb - Long Range Climb

ranged from sea level to FL300 in 3048 m (10,000 ft) increments. Speeds were chosen to span the normal range of operations expected at each specified weight and altitude. The lowest speed value selected was near the 1.3 g buffet boundary; the middle speed value was near the normal operating speed for the aircraft and the high speed value was at or near the maximum FAA authorized speed as shown in the performance handbook. The cruise validation data is shown in Figures 5.36, 5.37, 5.38 and 5.39. It can be noted that some differences between the handbook data and the model exist. These differences are primarily due to the assumption that fuel flow is proportional to thrust for a given Mach number. Very likely, a refinement of this assumption to reflect the effect of changes in air densities could improve the model performance. However, since the model was to be exercised mainly in climbing and descending control modes, the cruise data variations from the handbook values were not considered to be serious enough to warrant further refinement.

The descent validation for the DC-10 consisted of data taken for two aircraft weights, 108,862 and 163,293 Kg (240,000 and 360,000 lbs) and two descent procedures, high speed and long range descent. The high speed descent consisted of a constant Mach number descent at .85 until an indicated airspeed of 175 m/s (340 kt) was reached at an altitude near FL270, then a constant IAS descent was maintained to 3048 m (10,000 ft) where a level altitude deceleration to 129 m/s (250 kt) was performed. The latter speed was maintained until the aircraft reached sea level. The time, distance and fuel to descend for the high speed descent are shown in Figure 5.40. The data collected from the model is in close agreement with the data shown in the performance handbook.

The long range descent consists of a deceleration at cruise altitude to 129 m/s (250 kt) followed by a constant IAS descent to sea level. Again, as with the high speed descent case, two weight values were used in the descent analysis. The results of the long range descent validation are shown in Figure 5.41. The results are in close agreement with the handbook values throughout the entire range of descent altitudes.

0 - Validation Point

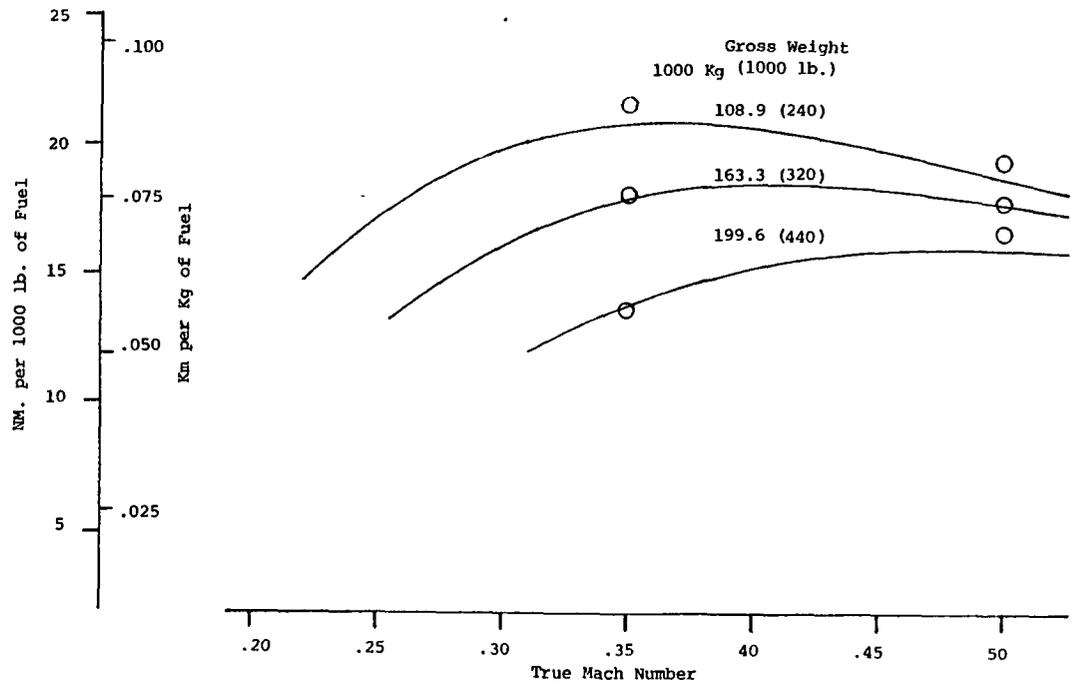


Figure 5.36 DC-10 Specific Range, Sea Level

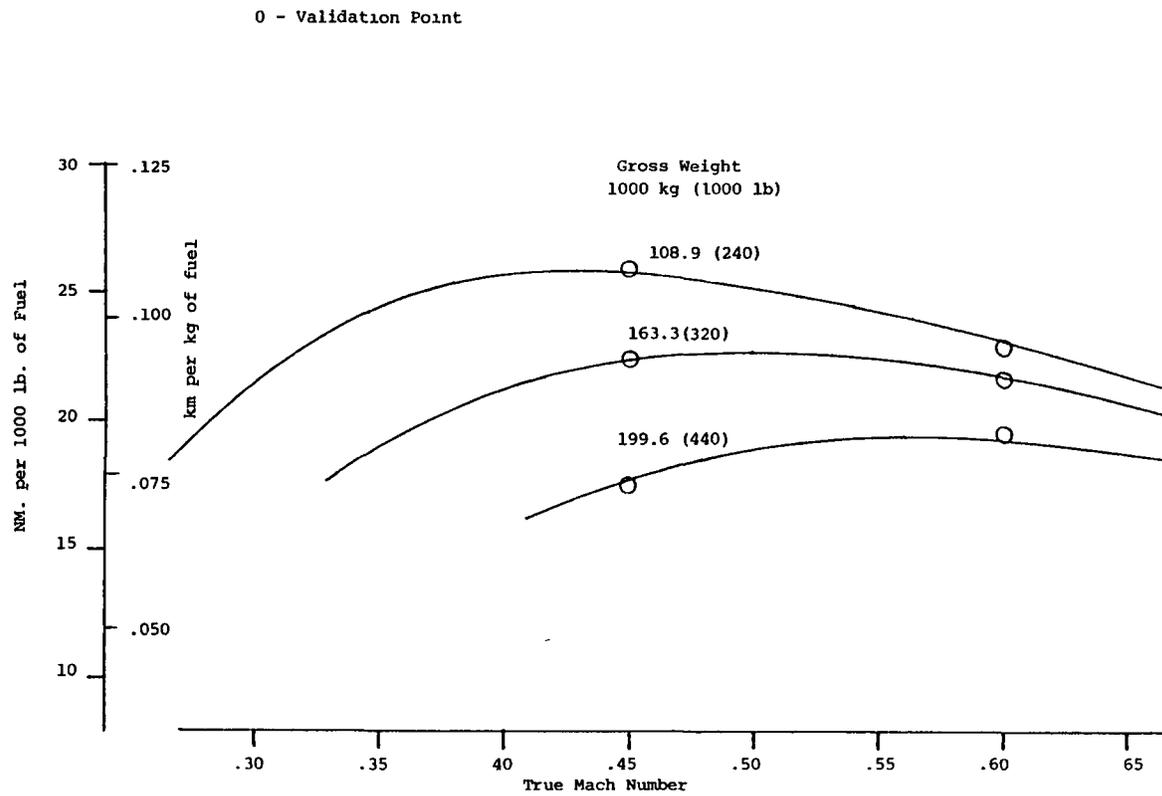


Figure 5.37 DC-10 Specific Range, 3048 m (10,000 ft)

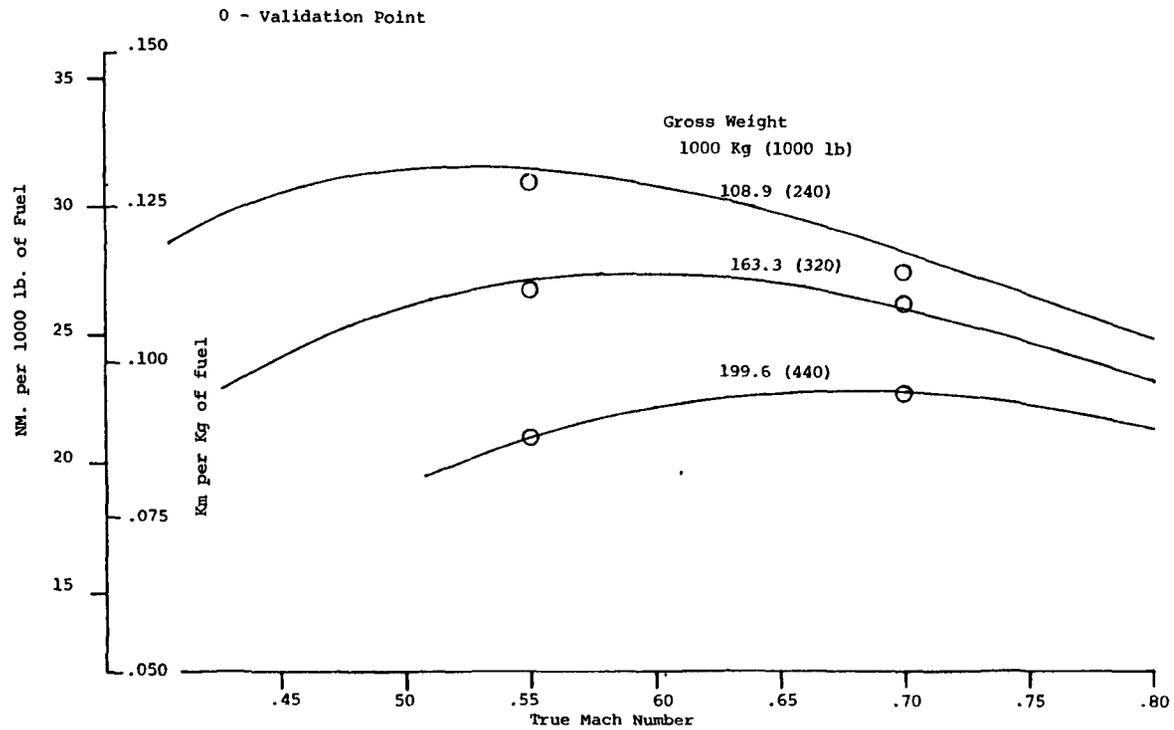


Figure 5.38 DC-10 Specific Range, 6096 m (20,000 ft)

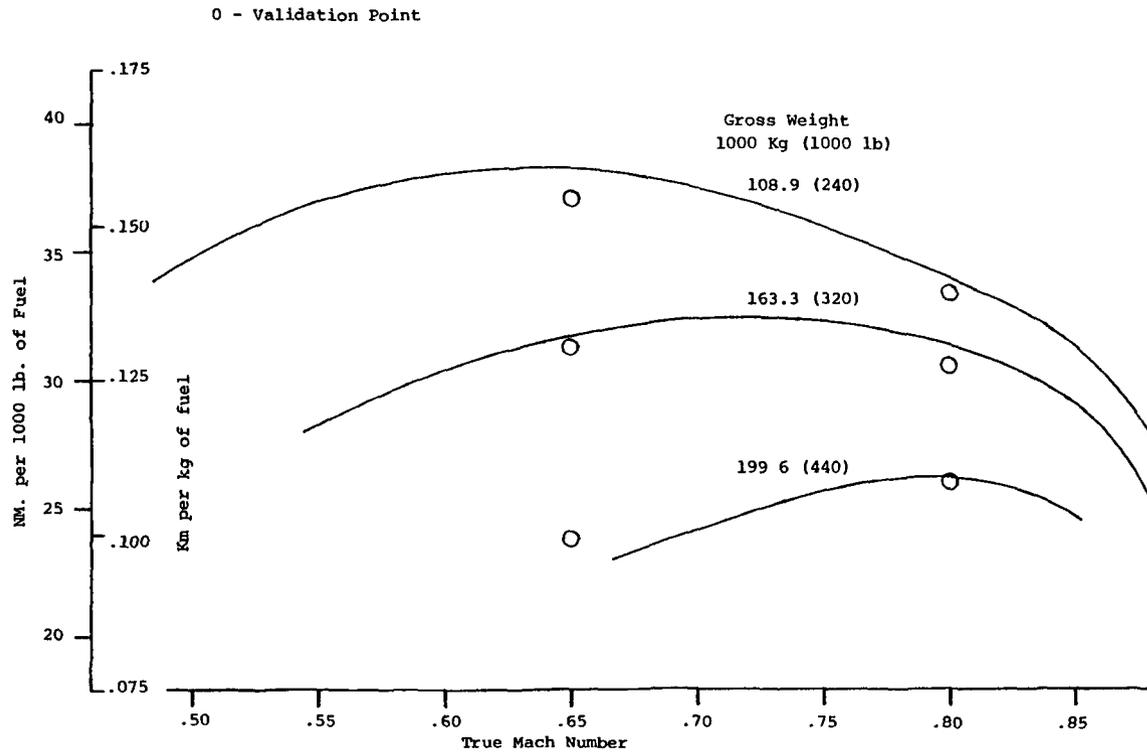


Figure 5.39 DC-10 Specific Range, 9144 m (30,000 ft)

0 - Validation Point

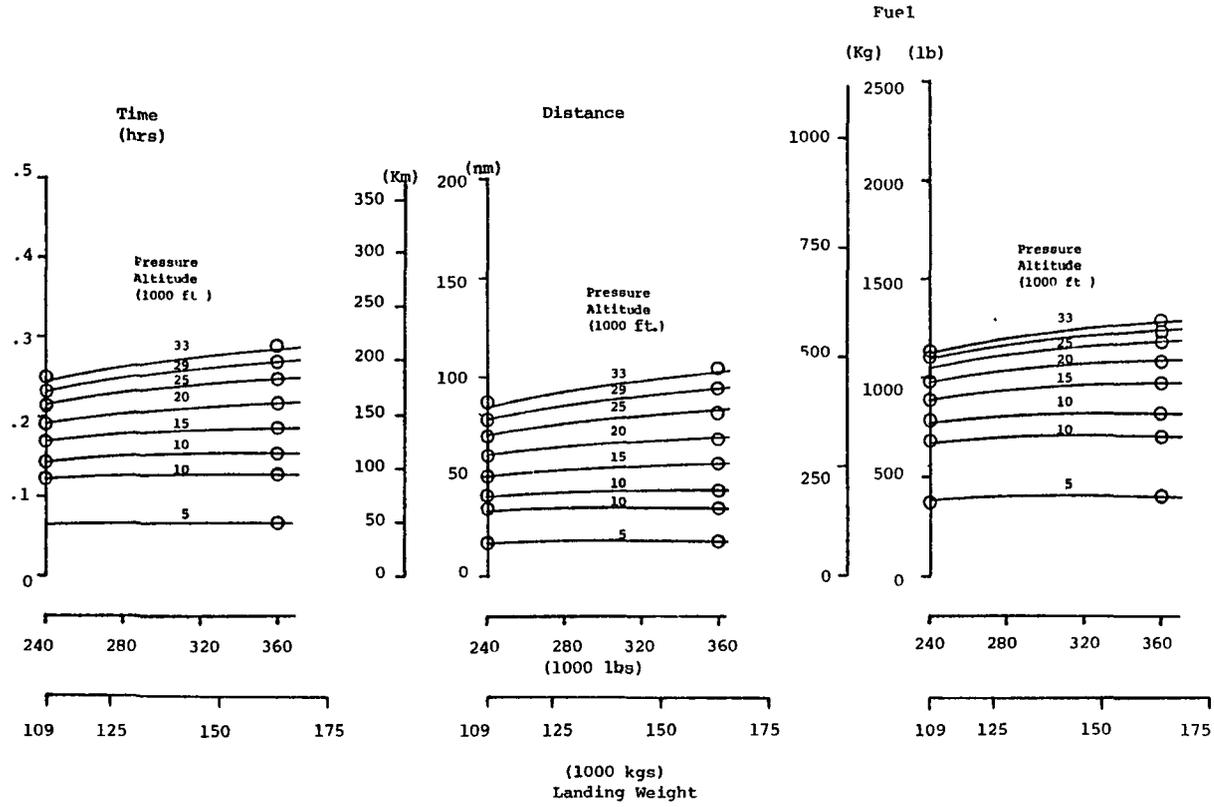


Figure 5.40 DC-10 Distance and Fuel to Descent, High Speed Descent

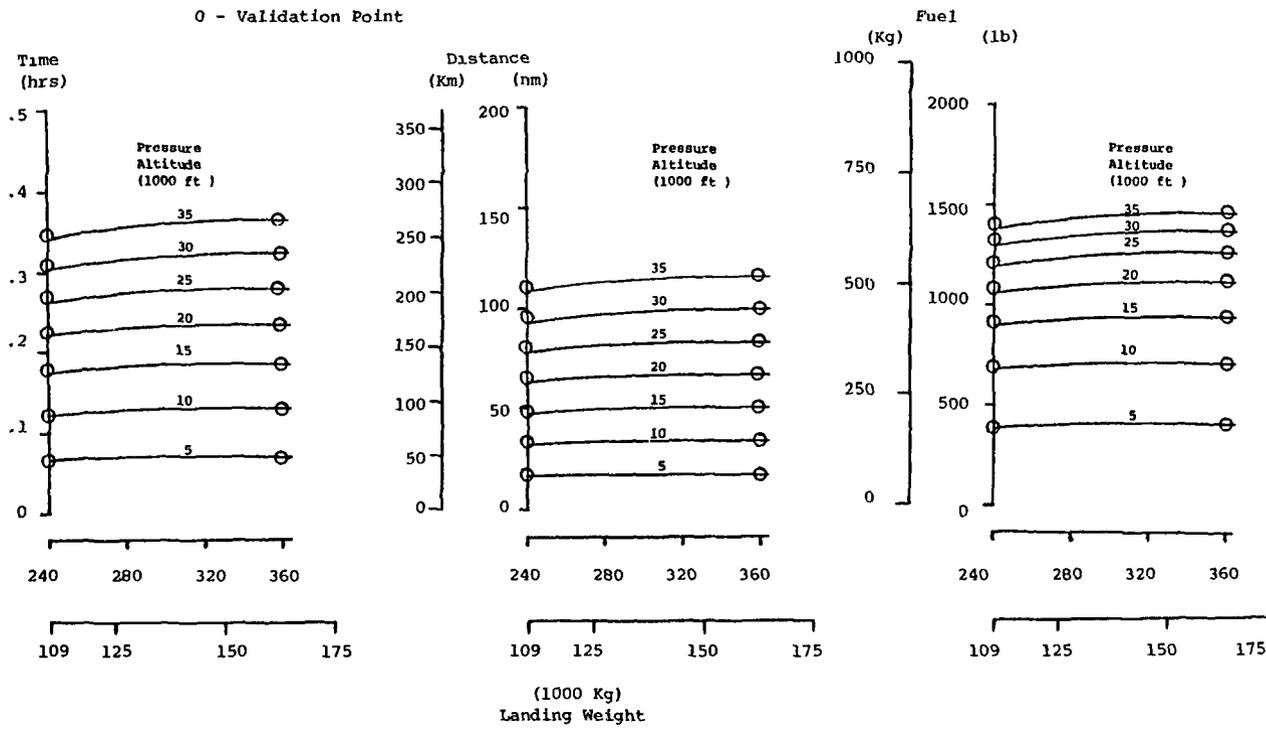


Figure 5.41 DC-10, Time, Distance and Fuel to Descent, Long Range Descent

### 5.3 AIRCRAFT TIME AND FUEL BENEFITS

The models of the B737 and DC-10 were used to complete the information concerning standard climb procedures and to collect data on the ability of different climb procedures to provide improved values for aircraft time and/or fuel to climb and descend. The standard procedures included climbs and descents using the following combinations of aircraft profile control:

- constant indicated airspeed at full climb or idle thrust
- constant Mach number at full climb or idle thrust
- acceleration/deceleration at level altitude at full climb or idle thrust
- constant Mach number with throttled thrust at a specified flight path angle
- constant indicated airspeed with throttled thrust at a specified flight path angle
- constant rate of climb or descent with full climb or idle thrust

All of the above procedures may be executed with instrumentation that is found on all air carrier aircraft. The use of alternative flight control techniques during climb and descent was investigated in the second part of the data collection effort. The purpose for using these alternate control techniques was to determine if any additional time, fuel and economic benefits could be obtained through the use of these procedures. These procedures included those listed previously plus the following additional control modes:

- constant change in Mach number with respect to a change in altitude at full climb or idle thrust
- constant change in indicated airspeed with respect to a change in altitude at full climb or idle thrust
- constant flight path angle at full climb, throttled or idle thrust

These techniques represent changes which could be incorporated by modifying the aircraft flight control system but retaining the same basic navigation and air data system. The use of the constant flight path angle would require the use of a VNAV computer that could be used with the aircraft's present VOR/DME or inertial navigation system.

The data collection task involved the preparation of several sets of input data for the aircraft performance model, the processing of the input data, and the recording of the output of the computer program in terms of time and fuel required by the aircraft to reach a specified final state. In the climb cases the following initial and final states were selected:

#### B737 Initial State

Altitude		3048 m (10,000 ft)
Distance	-	0 km (0 nm)
Time	-	0 minutes
Fuel	-	0 Kg (0 lbs.) consumed
Speed	-	129 m/s (250 kt) indicated airspeed

#### B737 Final State

Altitude	-	8,839 m (29,000 ft)
Distance	-	370 Km (200 nm)
Time	-	As required by procedure
Fuel	-	As required by procedure
Speed	-	Mach 0.78

#### DC10 Initial State

Altitude	-	3048 m (10,000 ft)
Distance	-	0 Km (0 nm)
Time	-	0 minutes
Fuel	-	0 Kg (0 lbs)
Speed	-	129 m/s (250 kt) indicated airspeed

#### DC-10 Final State

Altitude	-	10,668 m (35000 ft)
Distance	-	556 Km (300 nm)
Time	-	As required by procedure
Fuel	-	As required by procedure
Speed	-	Mach 0.85

The aircraft state for descents inverted the initial and final state values for each aircraft. No attempt was made to determine performance values for altitudes lower than 3048 m (10,000 ft) nor at speeds below 129 m/s (250 Kt) since the effects of auxiliary lift and drag devices such as flaps, slats, spoilers and landing gear were not modeled.

The cost benefit or penalty associated with the use of each of the flight procedures was computed by using a cost per flight minute and a cost per pound of fuel multiplier for the time and fuel benefits or penalties. The aircraft cost multipliers were obtained from CAB aircraft operating cost records for the year 1973 [Reference 36]. The cost per flight minute was estimated from an average (weighted by the number of aircraft in use) of the costs for each of the airlines operating that type of aircraft. Airlines used included both trunk and local service carriers. A high and a low value of operating cost was computed by using the total cost per flight hour less fuel for the high value and the total cost per flight hour less fuel and depreciation for the low value. Two values for fuel costs were also used. A low value of \$.11/Kg (\$.05/lb) was used as a price representative of airlines which have long term fuel contracts with suppliers. A high fuel value of \$.22/Kg (\$.10/lb) was used to represent the price determined from local suppliers of JP-4 in the West Palm Beach, Florida area. These prices represent current market prices for fuel but 1973

values for operating cost per flight minute. In order to bring the 1973 prices up to 1976 a multiplier of 1.17 was used on the operating costs which represents a 5.5%/year rate of inflation. The final operating and fuel costs used in the analysis were as follows:

B737 Costs

Operating cost - high	\$10.69/flight minute
Operating cost - Low	\$ 8.18/flight minute

DC-10 Costs

Operating cost - high	\$24.15/flight minute
Operating cost - low	\$14.44/flight minute

Fuel Cost

Fuel cost - high	\$.22/Kg (\$0.10/lb)
Fuel cost - low	\$.11/Kg (\$0.05/lb)

These cost values are included so that some relative economic value can be associated with the use of that specific procedure. It is well known that other factors influence the particular choice of a procedure such as weather, fuel reserves, ATC requests, etc. Consequently, the cost benefit or penalty should not be used as the sole indicator of the relative worth of a specific procedure.

5.3.1 Boeing 737 Climb Analysis

In order to determine the time and fuel utilization for the Boeing B737-200 during climb, a total of sixty-seven climb cases were considered. Three different weight categories, 29,483 Kg (65,000 lbs), 40,823 Kg (90,000 lbs) and 52,163 Kg (115,000 lbs) were processed for analysis. For the heavy weight and the light weight aircraft twenty cases using five different control procedures were performed. At medium weight, twenty-seven cases were analyzed. These cases consisted of the climb procedures described in Table 5.1. The first sixty-one cases were selected in a manner such as to cover the range of speed

**Table 5.1**  
**B737 Climb Cases**

CONTROL VALUE						
CONTROL MODE	Case #	29,483 Kg (65,000 lbs)	Case #	40,823 Kg (90,000 lbs)	Case #	52,163 Kg (115,000 lbs)
Constant IAS Standard Climb Procedure M/S (Kt)	1	134 (260)	6	134 (260)	12	134 (260)
	2	144 (280)	7	144 (280)	13	144 (280)
	3	154 (300)	8	149 (290)	14	154 (300)
	4	167 (325)	9	154 (300)	15	167 (325)
	5	180 (350)	10	167 (325)	16	180 (350)
Constant $dV_I/dH$ From 129 M/S (250 Kt) IAS to Cruise Altitude KMPH/KM(Kt/1000')	17	12.2 (2)	21	12.2 (2)	25	12.2 (2)
	18	24.3 (4)	22	24.3 (4)	26	24.3 (4)
	19	36.5 (6)	23	36.5 (6)	27	36.6 (6)
	20	48.6 (8)	24	48.6 (8)	28	48.6 (8)
Constant $dM/dH$ from 129 M/S (250 kt) IAS to Cruise altitude $dM \times 10^6 / M$ (Ft)	29	59.1 (18)	34	59.1 (18)	39	59.1 (18)
	30	62.3 (19)	35	62.3 (19)	40	62.3 (19)
	31	65.6 (20)	36	65.6 (20)	41	65.6 (20)
	32	68.9 (21)	37	68.9 (21)	42	68.9 (21)
	33	72.2 (22)	38	72.2 (22)	43	72.2 (22)
Constant $dV_I/dH$ from X M/S (Kt) IAS to Cruise Altitude KMPH/KM (Kt/1000 ft)	X = 154 (300)					
	44	-43.1 (-7.1)	47	-28.9 (-4.75)	50	-14.3 (-2.35)
	X = 167 (325)					
	45	-51.0 (-8.4)	48	-36.8 (-6.05)	51	-22.5 (-3.7)
	X = 180 (350)					
	46	-52.7 (-9.50)	49	-44.7 (-7.35)	52	-28.9 (-4.75)
Constant $dM/dH$ From X M/S (Kt) IAS to Cruise Altitude $dM \times 10^6 / M$ (Ft)	X = 154 (300)					
	53	-6.9 (-2.1)	56	15.6 (4.75)	59	36.1 (11.0)
	X = 167 (325)					
	54	-15.4 (-4.7)	57	6.9 (2.10)	60	27.6 (8.40)
	X = 180 (350)					
55	24.1 (-7.35)	58	0.0 (0.0)	61	18.9 (5.75)	
Constant $dV_I/dH$ from 149 M/S (290 Kt) IAS to Cruise Altitude KMPH/KM (Kt/1000 ft)			62	-12.8 (-2.1)		
			63	0.0 (0.0)		
			64	3.19 (525)		
Constant $dV_I/dH$ from 149 M/S (290 kt) IAS Altitude $dM \times 10^6 / M$ (Ft)			65	0.0 (0.0)		
			66	30.6 (9.32)		
			67	42.7 (13.0)		

vs altitude profiles that are within the performance limits of the B737 aircraft. The first sixteen cases are procedures which may be flown using conventional aircraft instrumentation. These cases provide a baseline with which the techniques involving modified control principles could be evaluated. Cases 17 through 67 use some selected combination of modified vertical control in some phase of the flight envelope. Cases 62-67 were selected to investigate the benefits of using modified control techniques in order to obtain minimum fuel climbs for the medium weight aircraft.

The results of the data runs are shown in Figures 5.42, 5.43 and 5.44 for each selected weight value. The graphs are presented in terms of time and fuel benefits as compared to a standard baseline case. The baseline cases were the standard procedure cases of a constant 167 m/s (325 kt) indicated climb (cases 4, 10 and 15). These baseline cases are associated with typical high speed climb techniques.

The results shown on these three graphs indicate that minimum time to climb can be associated with the highest speed standard climbs (Cases 5, 11 and 16). Minimum fuel to climb is definitely dependent upon the selected airspeed during climb. The optimum fuel values for the various weight aircraft are interpolated from the data as follows:

29,483 Kg (65,000 lbs)	-	139 m/s (270 kt), IAS
40,823 Kg (90,000 lbs)	-	149 m/s (290 kt), IAS
52,163 Kg (115,000 lbs)	-	153 m/s (297 kt), IAS

In addition to the time and fuel data, two zero dollar cost lines have been drawn on Figures 5.42, 5.43 and 5.44. These cost lines show the relative tradeoffs that can be made for time savings versus fuel savings by using the cost values for each quantity that is described in Section 5.3. The slope of

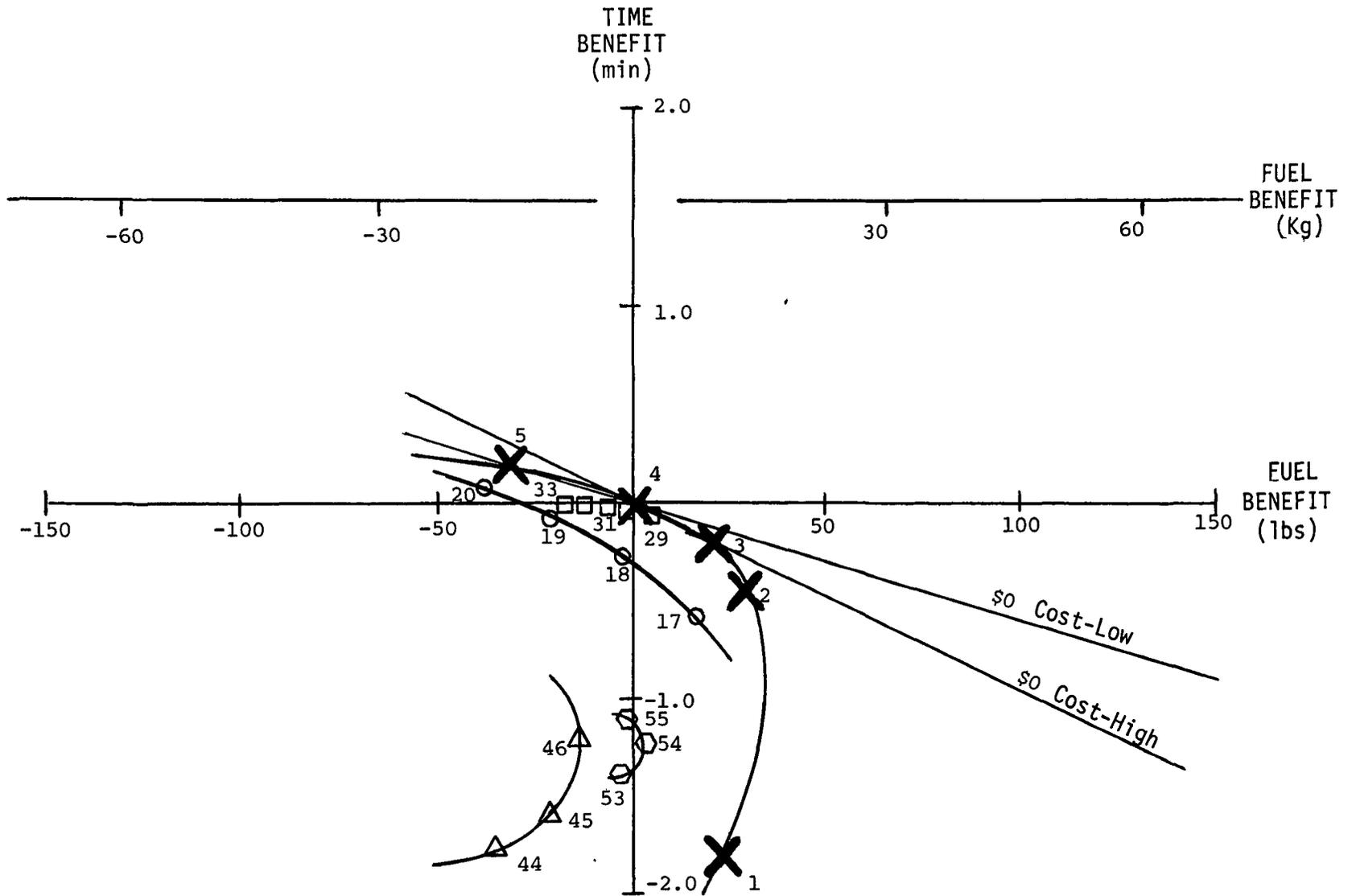


Figure 5.42 B737 Time and Fuel Benefits, 29,483 Kg (65,000 lb) Aircraft

X - Standard

O -  $DV_I/DH$

□ -  $DM/DH$

▽ -  $DV_I/DH$  with acceleration

⬡ -  $DM/DH$  with acceleration

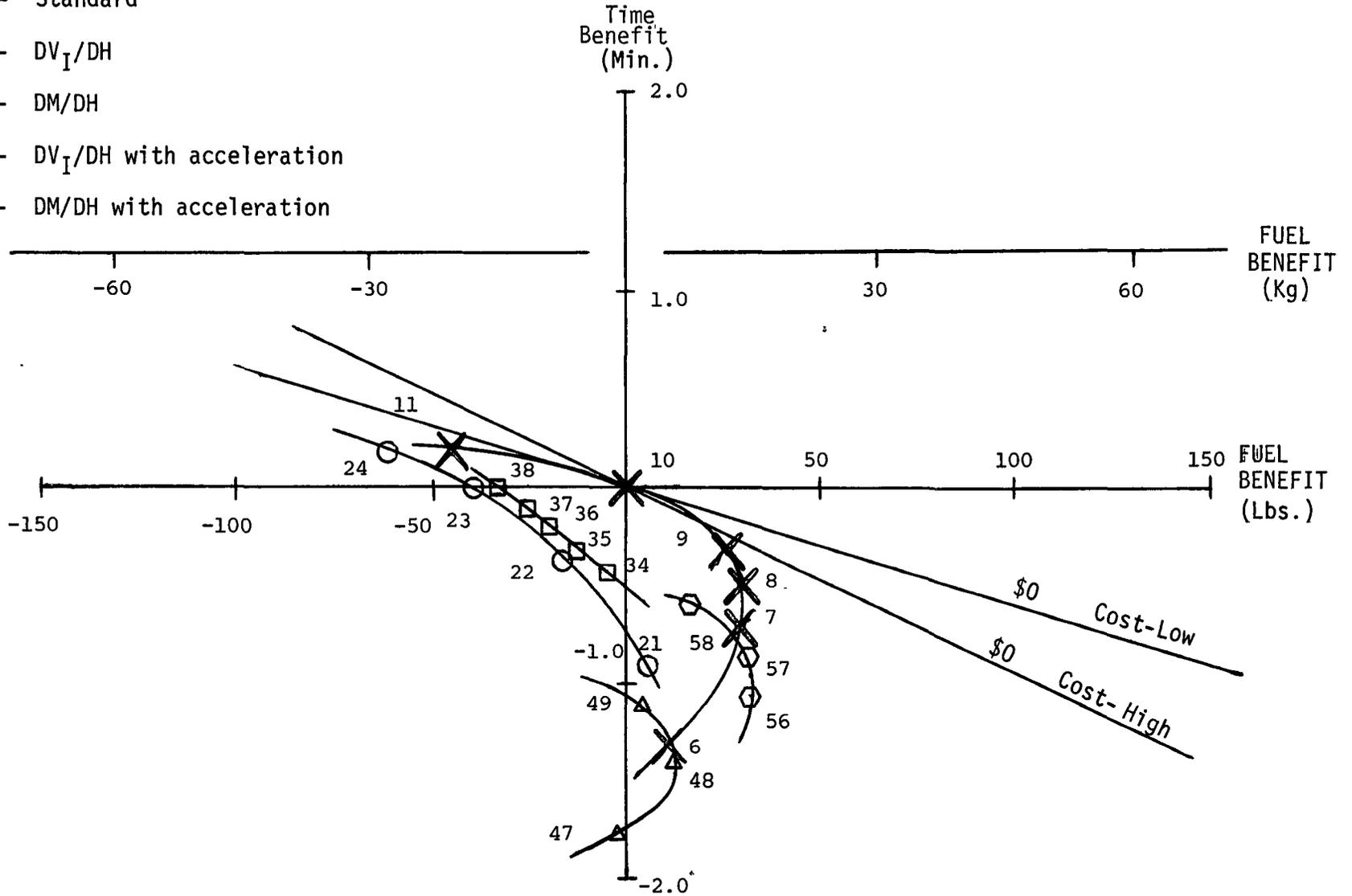


Figure 5.43 B737 Time and Fuel Benefits, 40,823 Kg (90,000 lb) Aircraft

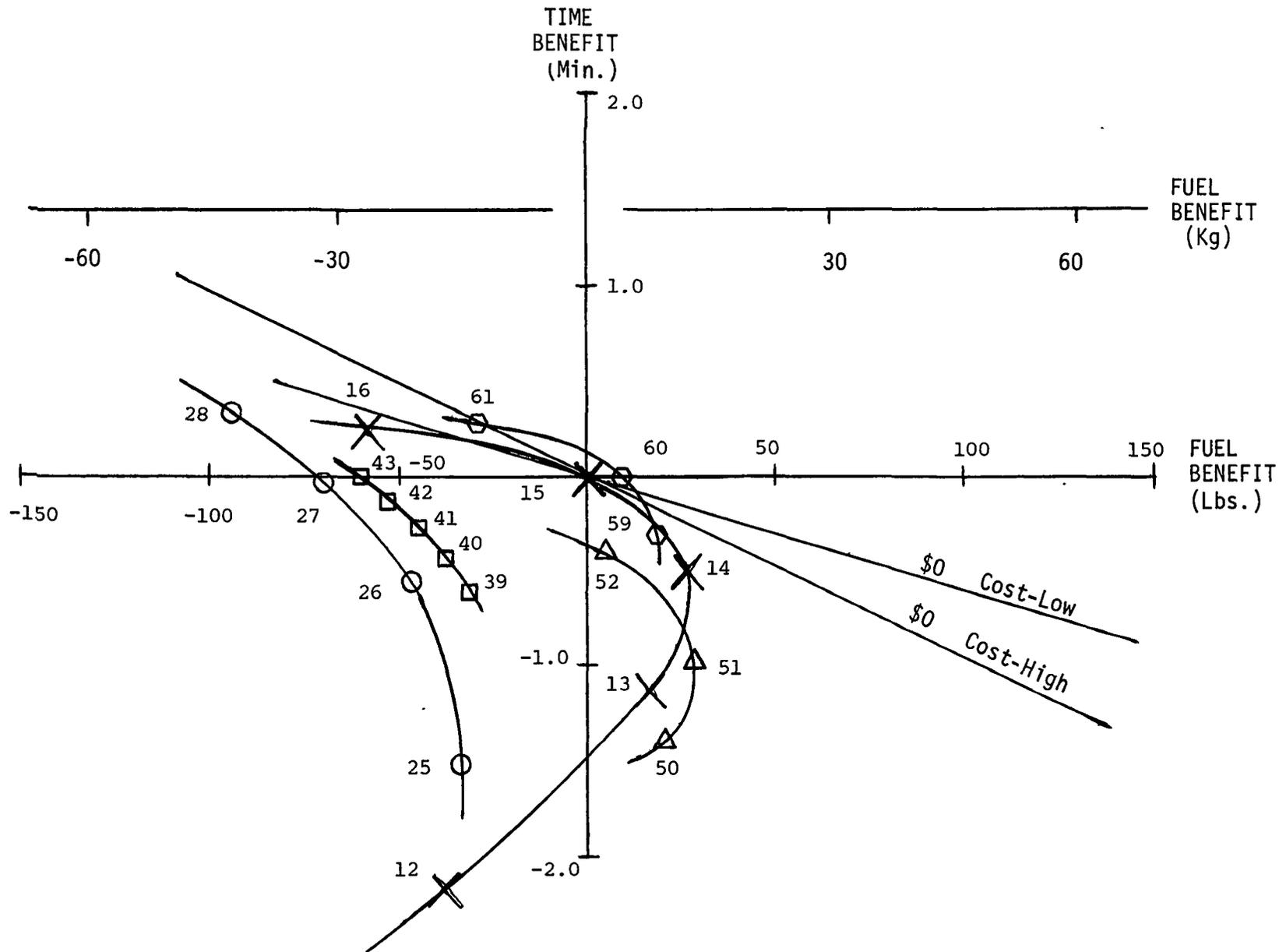


Figure 5.44 B737 Time and Fuel Benefits, 52,163 Kg (115,000 lb) Aircraft

each line is determined as follows:

$$\text{Slope, high} = - \frac{\text{operating cost, high}}{\text{fuel cost, high}}$$

$$\text{Slope, low} = - \frac{\text{operating cost, low}}{\text{fuel costs, low}}$$

The high and low values refer to costs computed in the following manner:

- operating cost, high - cost of operations per flight hour less fuel
- operating cost, low - cost of operations per flight hour less fuel and depreciation
- fuel cost, high - prices quoted by local suppliers for JP-4 jet fuel, spring 1976
- fuel cost, low - prices paid by airlines having long term fuel contracts with suppliers

Again as with the time and fuel benefits, the baseline cost value results from the high speed climb cases at an IAS of 167 m/s (325 kts) (Cases 4, 10 and 15). Values above and to the right of the \$0 cost line will be more cost beneficial than the baseline case while values below and to the left of the curves will be less cost effective than the baseline. It may be observed from Figures 5.42 and 5.43 that the baseline case is more cost effective than any of the other climb procedures. However, for the heavier weight aircraft in Figure 5.44 the dM/dH climb after an initial acceleration to an IAS of 167 m/s (325 kts) (Case 60) was slightly more cost effective than the baseline case (Case 15). This savings represents approximately \$1.50 for the high cost values and \$1.05 for the low cost values.

For the medium and heavy aircraft cases, the modified control techniques produced values for fuel benefit that were equal to or slightly greater than that for the standard climbs but at a significantly greater time penalty. For the

40,823 Kg (90,000 lb) aircraft, the  $dM/dH$  cases produced fuel savings slightly greater than the standard climb but at a time penalty of 0.6 minutes greater than the standard case (Case 56 versus Case 8). For the 52,163 Kg (115,000 lb) aircraft the  $dV_I/dH$  cases following an acceleration to 167 m/s (325 kt) produced the same fuel savings at a 0.4 minute greater time penalty than did the standard climb (Case 51 vs Case 14).

Although these cases using modified climb procedures involve greater time penalties than do the standard cases and would thus appear to be less desirable, the time penalty can actually be used to some advantage in certain ATC situations. These situations occur when the aircraft is expected to encounter a known delay of a specified amount of time. The modified climb procedure can provide all or part of that known delay at no significant fuel penalty from the optimum fuel consumption value.

The region in the vicinity of the standard climb fuel optimum point for the 40,823 Kg (90,000 lb) aircraft (Case 8) was examined further to pursue this observation. Six additional cases were performed using the modified control procedures, three  $dV_I/dH$  cases and three  $dM/dH$  cases. The results of these cases are shown in Figure 5.45. It can be seen from these curves that the modified procedures produced improved fuel savings at a greater time penalty than do the standard climb procedures. The aircraft can be delayed up to one minute in time with no significant reduction in fuel consumption by using the modified climb procedure (Case 62 vs Case 8).

### 5.3.2 Boeing 737 Descent Analysis

Forty descent cases were analyzed for the Boeing 737. Two weights of 29,483 Kg (65,000 lbs) and 40,813 Kg (90,000 lbs) were used in the descent analysis. Four types of descent procedures were considered. These procedures consisted

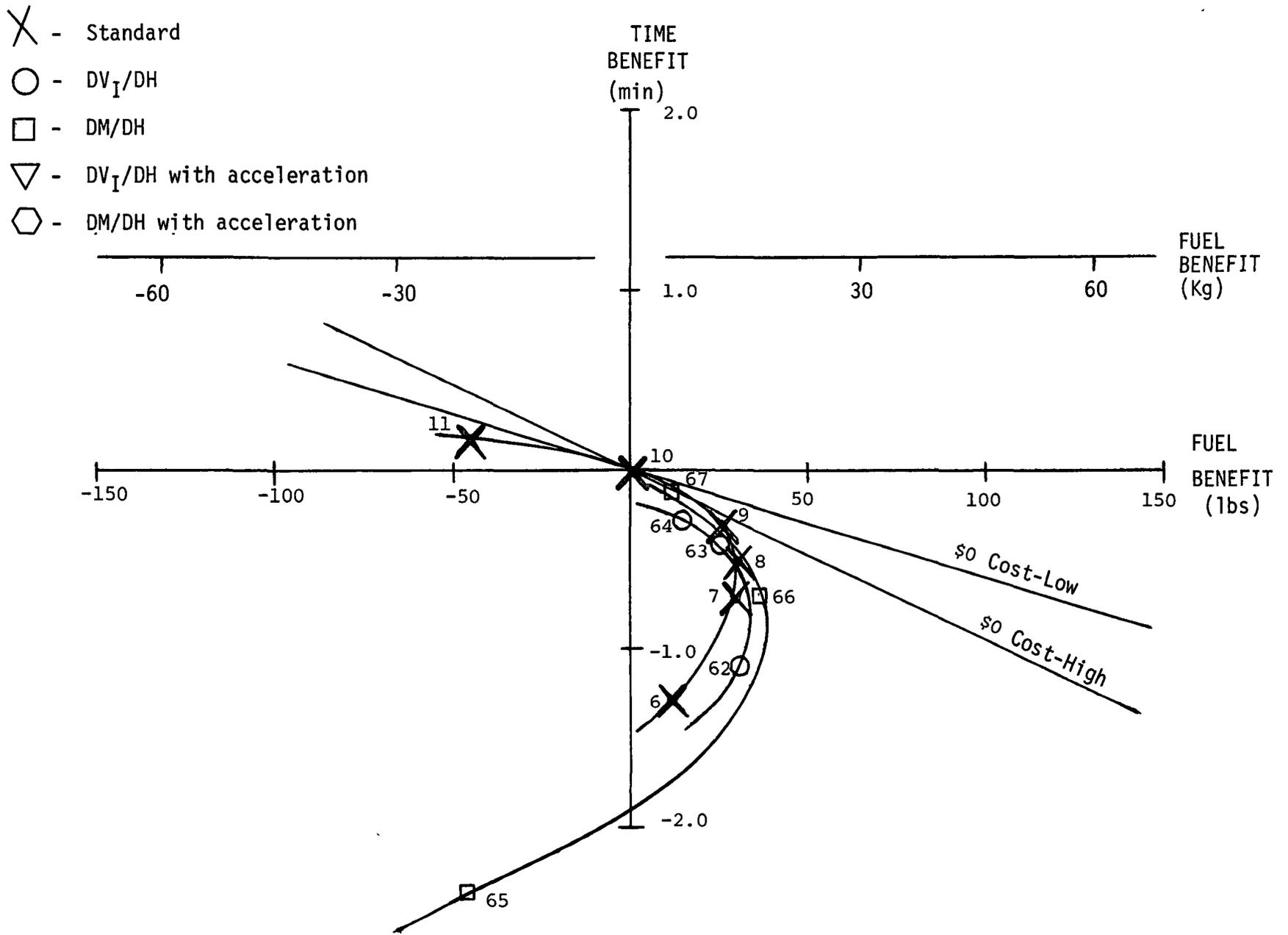


Figure 5.45 B737 Time and Fuel Benefits, 40,823 Kg (90,000 lb) Aircraft Optimum Fuel Consumption Cases

of standard constant indicated airspeed, VNAV,  $dV_I/dH$  and  $dM/dH$  descents. The case numbers and control values used in the descent analysis are shown in Table 5.2. The results in terms of time, fuel and cost benefits are shown in Figures 5.46 and 5.47. The baseline cases were chosen to be the high speed descent cases at 180 m/s (350 kt) (Cases 5 and 10). It may be observed that the descent time-fuel benefits exhibit a much more linear behavior than do the climb cases. In most cases a time penalty is offset by a fuel savings with the ratio being approximately 1 minute/50 Kg (110 lbs) of fuel. Major exceptions to this linear behavior were the throttled VNAV descents at shallow flight path angles. These descents produced less fuel benefits than would be expected from the linear relationship. This phenomenon is probably caused by the aircraft flying at high speeds in the lower altitudes for a longer period of time due to the shallow descent angle (Cases 35 and 38). The differences in control procedures produces slight differences in benefits, for example, the  $dV_I/dH$  cases seem to be slightly less beneficial than do the standard descent cases, particularly at the slower airspeeds. However, none of these results differ significantly from the basic time fuel ratio of 1 minute/50 Kg (110 lbs) of fuel.

In terms of cost savings, the higher speed descents are more cost effective than the slow speed descents. This is shown on Figures 5.46 and 5.47 by the fact that most values from the descent analysis fall on or to the left of the \$0 cost lines for both the high and low cost values. This occurs because the cost ratio for time and fuel exceeds that of the basic time-fuel ratio. With a linear relationship between time and fuel benefits it is not possible to choose an optimum operating point as was the case for minimum fuel climb trajectories. If a known delay is encountered in the terminal area, the appropriate descent control values can be selected to obtain a fuel benefit. The procedure can be any of those that were analyzed in this investigation as most cases exhibited the same linear behavior.

Table 5.2

B737 Descent Cases

	CONTROL VALUE			
	Case #	29,483 Kg (65,000 lbs)	Case #	40,823 Kg (90,000 lbs)
Constant IAS Standard Descent Procedure M/S (Kt)	1	129 (250)	6	129 (250)
	2	141 (275)	7	141 (275)
	3	154 (300)	8	154 (300)
	4	165 (320)	9	165 (320)
	5	180 (350)	10	180 (350)
Constant $dV_I/dM$ Descent to 3048 M(10,000 Ft) KMPH/KM (Kt/1000 ft)	11	-15.2 (-2.5)	16	-15.2 (-2.5)
	12	- 7.3 (-1.2)	17	- 7.3 (-1.2)
	13	3.6 (0.6)	18	3.6 (0.6)
	14	7.3 (1.2)	19	7.3 (1.2)
	15	15.2 (2.5)	20	15.2 (2.5)
Constant $dM/dH$ Descent to 3048 M(10,000 Ft) $dM \times 10^6/M$ (Ft)	21	26.2 (8)	26	26.2 (8)
	22	32.8 (10)	27	32.8 (10)
	23	39.4 (12)	28	39.4 (12)
	24	45.9 (14)	29	52.5 (16)
	25		30	
VNAV at Idle Thrust	31	-4°	33	-4°
	32	-6°	34	-6°
VNAV at Constant 180 M/S(350 Kt) IAS	35	-2°	38	-2°
	36	-4°	39	-4°
	37	-6°	40	-6°

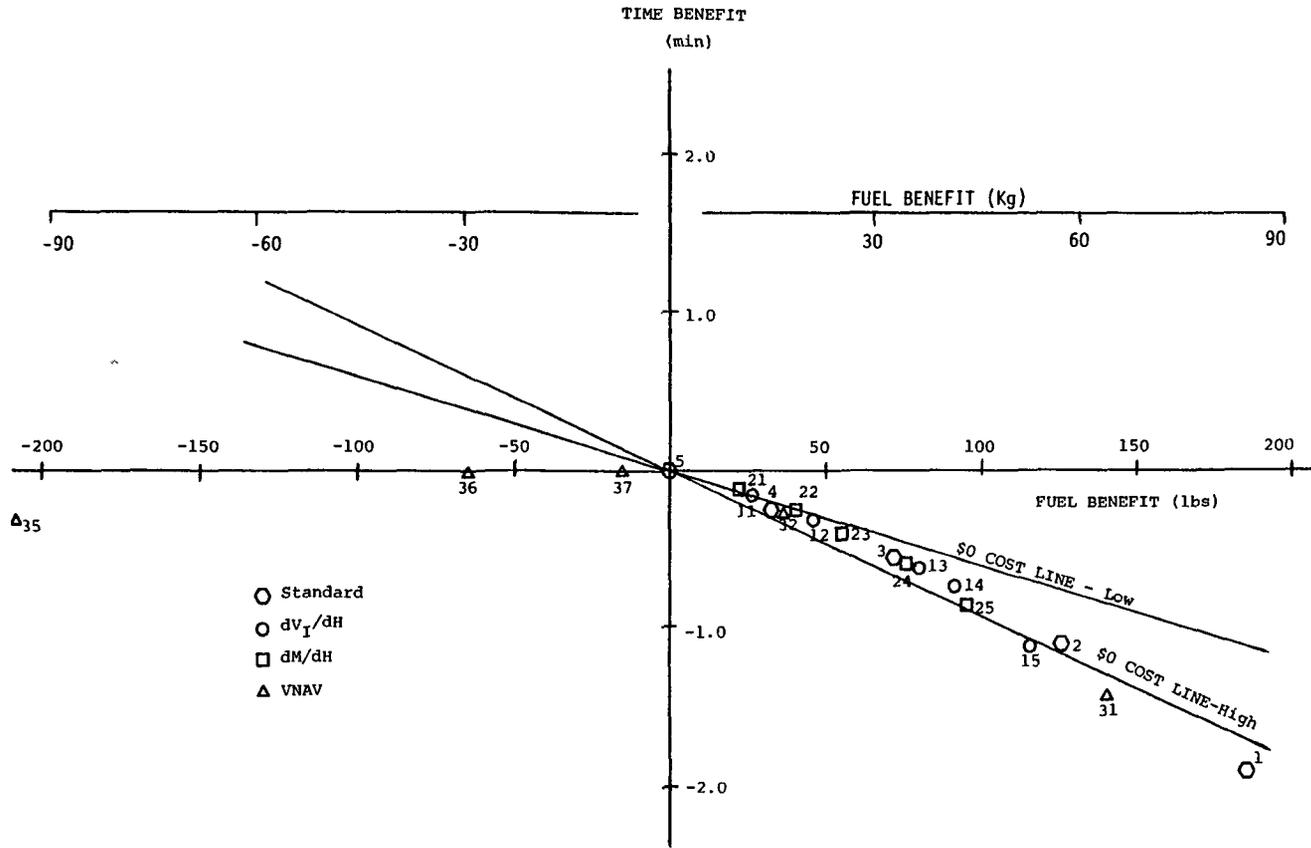


Figure 5.46 B737 Descent Time-Fuel Benefits, 29,483 Kg (65,000 lb) Aircraft

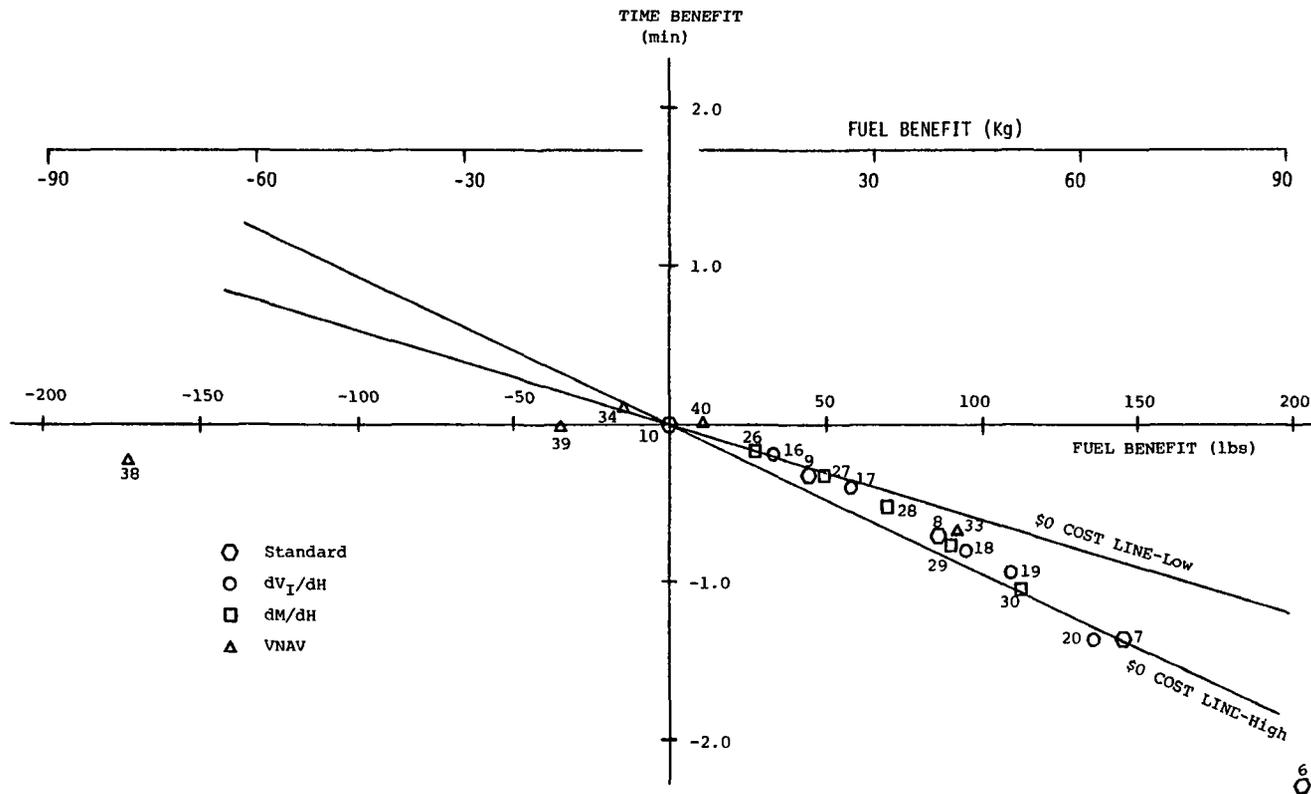


Figure 5.47 B737 Descent Time-Fuel Benefits, 40,823 Kg (90,000 lb) Aircraft

The only descent procedure that can be directly associated with geographical coordinates is the VNAV descent. This type of descent has definite advantages when operating in airspace that is unconstrained by ATC requirements and conflicting traffic such as low density terminal areas. In these areas the descent initiation points at the end of cruise may be positively identified through the use of the VNAV descent gradient. The other types of descent procedures are based upon airspeed and altitude relationships and are consequently affected by wind conditions along the flight path. No specific evaluation of the benefits associated with VNAV descents was undertaken since the benefits would depend upon knowing what methods are used for descent point determination in the non-VNAV descents. The determination of the descent point can vary widely from airline to airline and from pilot to pilot, therefore direct evaluations would be difficult to measure.

### 5.3.3 DC-10 Climb Analysis

The results of the climb analysis for the DC-10 aircraft essentially parallel those of the B737 with the magnitude of the benefits in proportion to the larger size of the DC-10. Forty-two climb cases, fourteen for each of the weights, were analyzed for the DC 10 climb. These cases are listed in Table 5.3. The three weights considered were 108,862 Kg (240,000 lbs), 163,293 Kg (360,000 lbs) and 199,581 Kg (440,000 lbs). These represent the range of weights within the operational limits of the DC-10. The baseline DC-10 climb case was a 175 m/s (340 kt) climb to a Mach number of 0.85 (Cases 5, 10 and 15). The results are shown in Figures 5.48, 5.49 and 5.50.

The minimum time to climb case that was considered was obtained by accelerating to maximum climb airspeed [175 m/s (340 kt)] to perform a constant IAS climb to Mach 0.85 and thereafter maintaining a constant Mach number climb to cruise altitude.

Table 5.3  
DC-10 Climb Cases

	CONTROL VALUE					
	Case #	108,862 Kg (240,000 lbs)	Case #	163,293 Kg (360,000 lbs)	Case #	199,581 Kg (440,000 lbs)
Constant IAS	1	134 (260)	6	134 (260)	11	134 (260)
Standard Climb	2	141 (275)	7	141 (275)	12	141 (275)
Procedure	3	154 (300)	8	154 (300)	13	154 (300)
M/S (Kt)	4	167 (325)	9	167 (325)	14	167 (325)
	5	175 (340)	10	175 (340)	15	175 (340)
Constant dV/dH	16	15.2 (2.5)	20	15.2 (2.5)	24	15.2 (2.5)
From 129 M/S(250	17	22.8 (3.75)	21	22.8 (3.75)	25	22.8 (3.75)
Kt) IAS to Cruise	18	45.6 (7.50)	22	45.6 (7.50)	26	45.6 (7.50)
Altitude KMPH/KM	19	68.4 (11.25)	23	68.4 (11.25)	27	68.4 (11.25)
(Kt/1000 ft)						
Constant dM/dH	28	55.8 (17)	32	55.8 (17)	36	55.8 (17)
From 129 M/S(250	29	65.6 (20)	33	65.6 (20)	37	65.6 (20)
Kt)IAS to Cruise	30	75.5 (23)	34	75.5 (23)	38	75.5 (23)
Altitude	31	85.3 (26)	35	85.3 (26)	39	85.3 (26)
dMx10 <sup>6</sup> /M (Ft)						
Constant dV/dH	40	-7.3 (-1.2)	44	-7.3 (-1.2)	48	-7.3 (-1.2)
Following	41	-11.5 (-1.9)	45	-11.5 (-1.9)	49	-11.5 (-1.9)
Acceleration to	42	-30.4 (-5.0)	46	-24.3 (-4.0)	50	-18.2 (-3.0)
123 M/S (240 Kt)	43	-48.6 (-8.0)	47	-36.5 (-6.0)	51	-24.3 (-4.0)
KMDH/KM(Kt/1000						
Ft)						
Constant dM/dH	52	-13.1 (-4)	56	6.6 (2)	60	19.7 (6)
Following Acceler-	53	9.8 (3)	57	164 (5)	61	23.0 (7)
ation to 175 M/S	54	29.5 (9)	58	29.5 (9)	62	29.5 (9)
(340 Kt)	55	36.1 (11)	59	36.1 (11)	63	36.1 (11)
dMx10 <sup>6</sup> /M (Ft)						

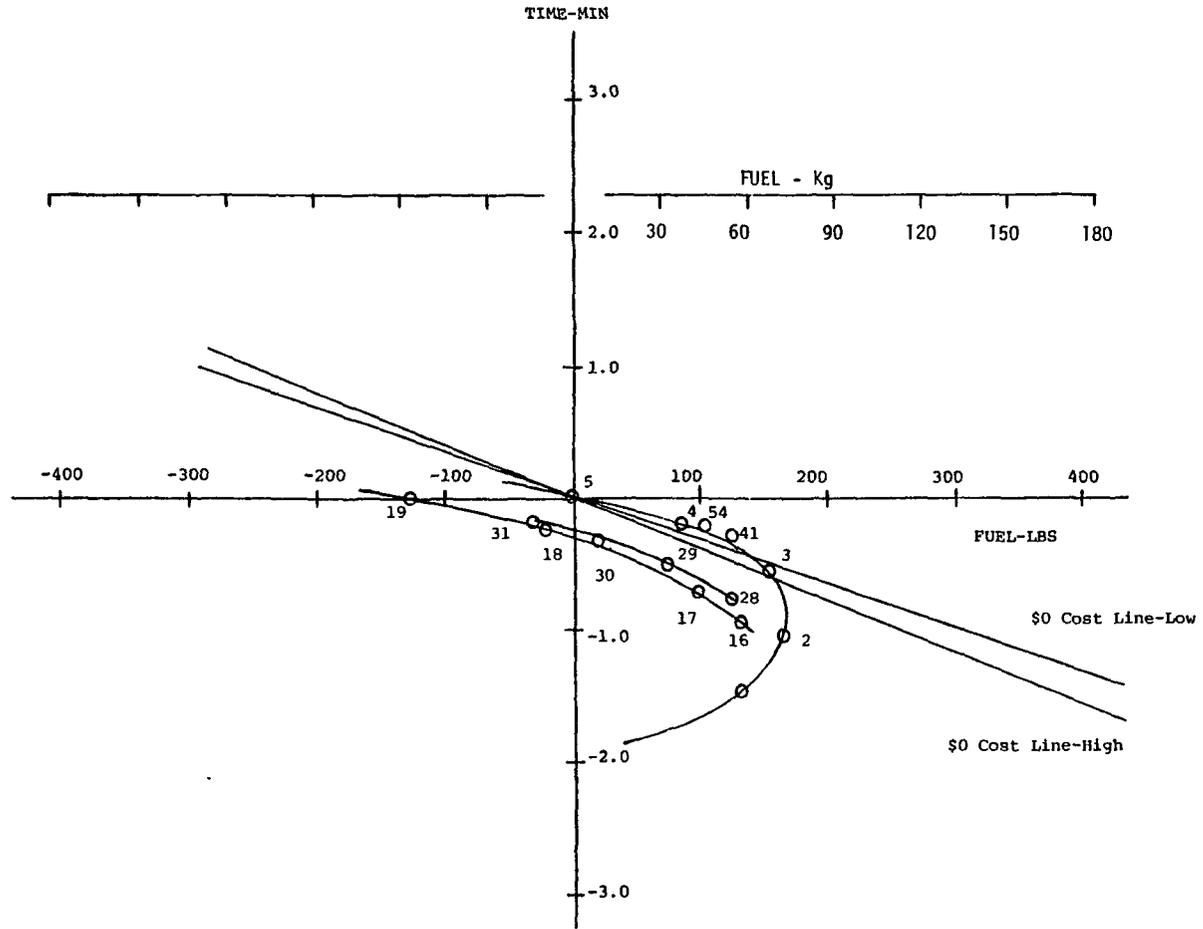


Figure 5.48 DC-10 Climb, Time-Fuel Benefit, 108,862 Kg (240,000 lb) Aircraft

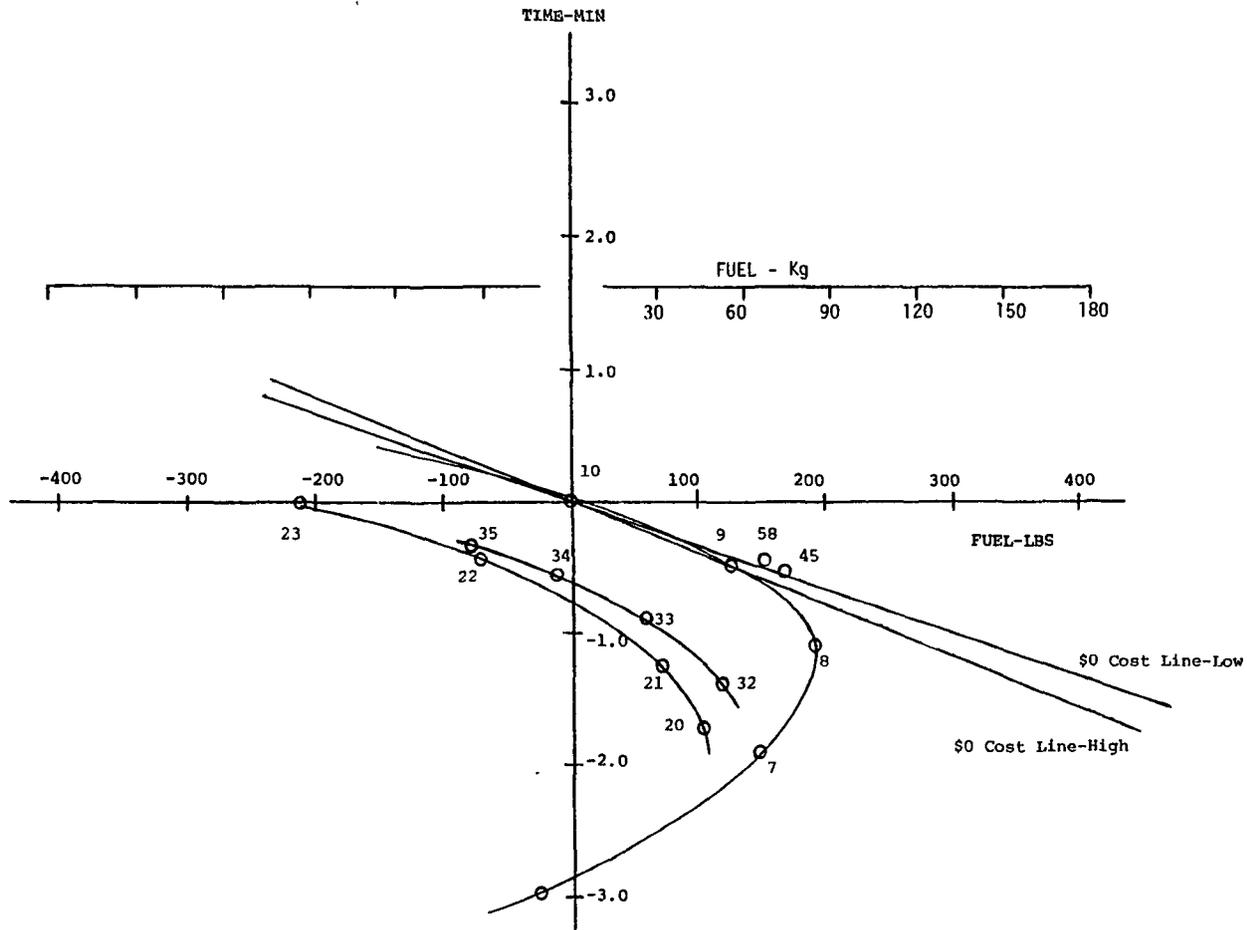


Figure 5.49 DC-10 Climb, Time-Fuel Benefit, 199,581 Kg (360,000 lb) Aircraft

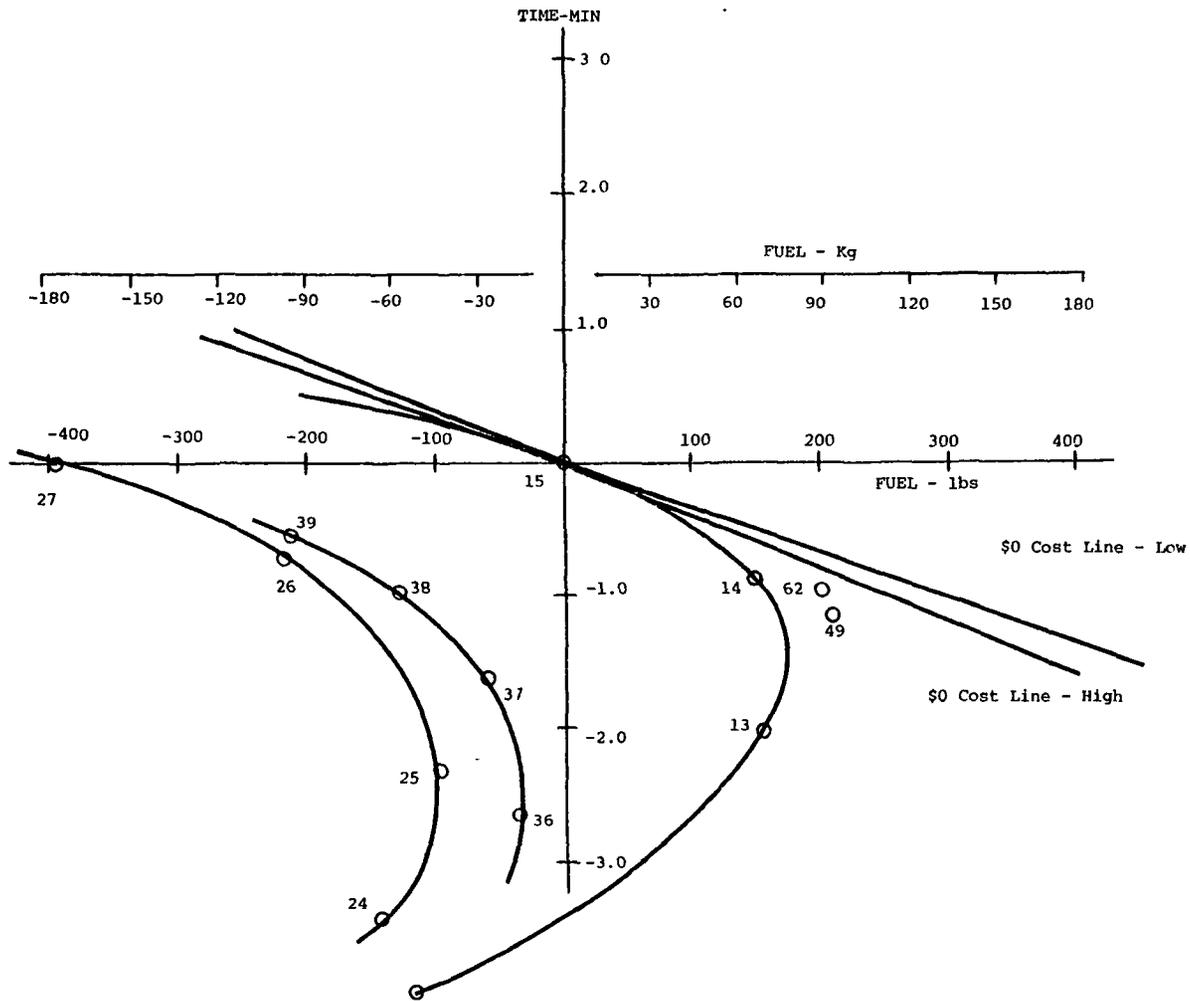


Figure 5.50 DC-10 Climb, Time-Fuel Benefit, 199,581 Kg (440,000 lb) Aircraft

The most fuel efficient standard IAS climb occurred at approximately the following speeds:

108,862 Kg (240,000 lbs) - 144 m/s (280 kt) IAS

163,293 Kg (360,000 lbs) - 153 m/s (298 kt) IAS

199,581 Kg (440,000 lbs) - 159 m/s (310 kt) IAS

For the light and medium weight aircraft this procedure represented the minimum fuel to climb value found in the results. For the heavy (440,000 lb) aircraft, the  $dV_I/dH$  and  $dM/dH$  climbs following an initial acceleration to 175 m/s (340 kt), provided slight fuel savings. All the  $dV_I/dH$  and  $dM/dH$  climbs starting at 129 m/s (250 kt) produced poorer fuel and time performance than did the standard climb. In situations where known ATC or other delays are encountered, the modified procedures can be used to provide a fuel optimum climb which can accommodate delays of up to 0.5, 0.6 and 1.1 minutes respectively for the light, medium and heavy DC-10 aircraft.

In terms of economic benefits, the high speed standard climb (Cases 5, 10 and 15) is near optimum for all three aircraft weights. Some slight economic benefit can be achieved through the use of the modified climb procedures. This improvement amounts to approximately \$1.70, \$2.90 and \$5.20 per climb for the light, medium and heavy aircraft.

#### 5.3.4 DC-10 Descent Analysis

As was the case for the DC-10 climb analysis, the results for the DC-10 descent cases essentially mimic those for the B737 descents with the magnitudes appropriately scaled to reflect the larger aircraft. Forty descent cases consisting of standard indicated airspeed, VNAV,  $dV_I/dh$  and  $dM/dH$  descents at two weight values were performed. The cases are shown in Table 5.4 and the results are pictured in Figures 5.51 and 5.52. The ratio of time benefits to fuel penalties for the light and medium weight aircraft are roughly 1 min/84 Kg (185 lbs) of fuel and 1 min/73 Kg (160 lbs) of fuel, respectively. Optimum fuel con-

Table 5.4

## DC-10 Descent Cases

	CONTROL VALUE			
	Case #	108,862 Kg (240,000 lbs)	Case #	163,293 Kg (360,000 lbs)
Constant IAS Standard Descent Procedure M/S (Kt)	1	129 (250)	6	129 (250)
	2	141 (275)	7	141 (275)
	3	154 (300)	8	154 (300)
	4	165 (320)	9	165 (320)
	5	175 (340)	10	175 (340)
Constant $dV_I/dH$ Descent To 3048 M(10,000 ft)KMPH/KM (Kt/1000 ft)	11	6.1 (1)	16	6.1 (1)
	12	12.1 (2)	17	12.2 (2)
	13	18.2 (3)	18	18.2 (3)
	14	24.3 (4)	19	24.3 (4)
	15	30.4 (5)	20	30.4 (5)
Constant $dm/dH$ Descent to 3048 M(10,000 ft) $dM \times 10^6/M$ (Ft)	21	45.9 (14)	26	45.9 (14)
	22	52.5 (16)	27	52.5 (16)
	23	59.1 (18)	28	59.1 (18)
	24	65.6 (20)	29	65.6 (20)
	25	72.2 (22)	30	72.2 (22)
VNAV at Idle Throttle	31	-4°	33	-4°
	32	-6°	34	-6°
VNAV at Constant 175 M/S(340KT)IAS	35	-2°	38	-2°
	36	-4°	39	-4°
	37	-6°	40	-6°

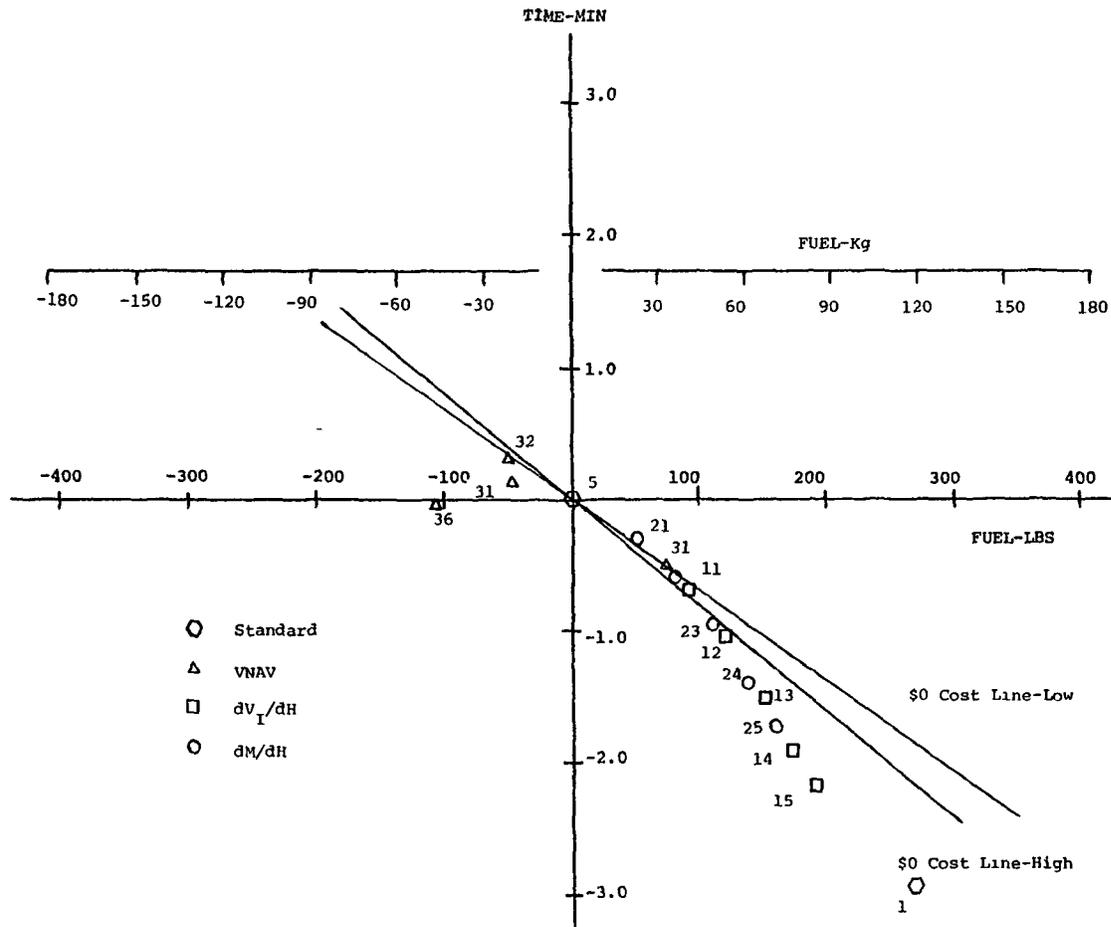


Figure 5.51 DC-10 Descent, Time-Fuel Benefit, 108,862 Kg (240,000 lb) Aircraft

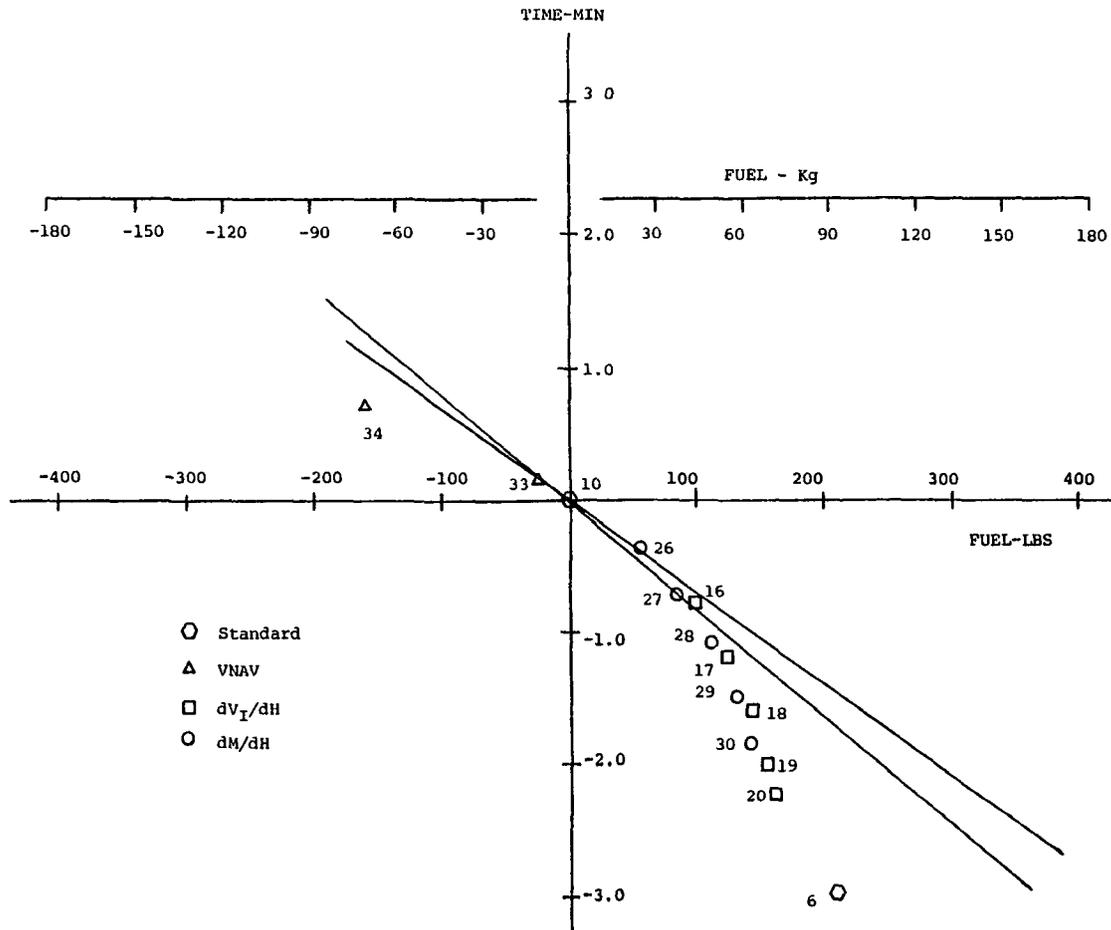


Figure 5.52 DC-10 Descent, Time-Fuel Benefit, 163,293 Kg (360,000 lb) Aircraft

sumption can only be obtained with a corresponding time penalty and vice versa. This relationship can be useful in saving fuel when known delays are anticipated in the terminal area. The throttled, low gradient VNAV descents (Cases 35 and 38) depart somewhat from the linear relationship between time and fuel benefits. Their relative benefit is somewhat less than the conventional and slower speed modified descents.

Regarding economic benefits, the high and low time/fuel ratios of 1 min/131 Kg (288 lbs) of fuel and 1 min/109 Kg (241 lbs) of fuel for the high speed descents exceed the tradeoff ratios of 1 min/84 Kg (185 lbs) of fuel and 1 min/73 Kg (160 lbs) of fuel for both the light and medium weight aircraft on the slower, fuel efficient descents. This indicates that, for the latter fuel economical descent procedures, relative time costs are more expensive than fuel costs.

#### 5.4 SUMMARY OF SECTION 5

The aircraft and flight control system simulation was applied to evaluate the deviations from the nominal curved approach path due to the system dynamics, measurement errors, and wind disturbances. In all of the above cases, no error greater than 38 m (125 ft) was observed along the simulated arc segment approach to runway 18 at Washington National. Also, for the geometry considered, it was observed that the heading error term in the control law was dominant in the case of a range measurement bias, while, for azimuth bias, the effect of the cross track deviation was most significant. Also, the experiment with wind effects indicated that relatively little advantage could be gained by continuously updating the command heading rate as variations in the groundspeed were sensed.

The models developed during this study for measuring aircraft performance for the DC-10 and B737 are capable of reproducing handbook time, distance and fuel values to an accuracy of 5% or greater in some cases. The climb and descent cases for the DC-10 exhibited an accuracy of 1% for all weight and profile types. Since the data analysis technique consists of determining baseline time, distance

and fuel values from the model and subtracting these values from other profile cases, any errors of the type noted above tend to cancel as long as the same model is used to compute both the data to be analyzed and the baseline data. For these purposes, both models were considered to provide acceptable performance data.

In general the DC-10 data is considered to be somewhat more reliable in terms representing the actual aircraft performance than the B737 data. This is due in part to the more comprehensive nature of the data presented in the DC-10 performance handbook. The performance data for the DC-10 was presented in the form of graphs that could be read to an accuracy of 1% to 2%. The B737 data was presented in the form of tables which contained values that were rounded to the nearest minute, nautical mile and hundred pounds of fuel. This lack of resolution in the B737 data tended to produce some greater differences in the B737 model and handbook profiles as compared to the DC-10. Overall, however, both the DC-10 and B737 models can produce acceptably accurate data for purposes of analyzing various climb and descent procedures.

The efficient energy management of the B737 and the DC-10 was considered for both climb and descent profiles. All comments are based upon block to block time and fuel benefits analyses where both the initial and final state were identical in terms of speed, altitude and distance for comparative cases. The term "standard climb" or "standard descent" shall refer to those climb and descent procedures which can be accomplished by conventional altitude, airspeed, and Mach number instrumentation. The term "modified climb" or "modified descent" will refer to a descent procedure which requires a change in the aircraft's instruments to produce  $dV_I/dH$  or  $d(\text{Mach})/dH$  profiles.

The major conclusions resulting from the energy management analysis that are described in the following paragraphs apply to both the B737 and the DC-10 unless specifically stated otherwise. All comments are based upon aircraft pro-

files between 3048 m (10,000 ft) and cruise altitude in which no auxiliary lift or drag devices such as flaps, speed brakes, etc., were used.

1. The minimum time to climb is achieved by accelerating the aircraft to its limiting airspeed value and thereafter climbing at that value until cruise altitude is reached.
2. The airspeed for minimum fuel consumption using standard climb procedures varies as a function of aircraft weight. The following values are representative of the airspeed for minimum fuel consumption:

B737

29,483 Kg (65,000 lbs) - 139 m/s (270 kt) IAS

40,823 Kg (90,000 lbs) - 149 m/s (290 kt) IAS

52,163 Kg (115,000 lbs) - 153 m/s (297 kt) IAS

DC 10

108,862 Kg (240,000 lbs) - 144 m/s (280 kt) IAS

163,293 Kg (360,000 lbs) - 153 m/s (298 Kt) IAS

199,581 Kg (440,00 lbs) - 159 m/s (310 kt) IAS

3. For light and medium weight aircraft the minimum fuel consumption can be achieved through the use of standard climb procedures. For heavy aircraft slight improvements in minimum fuel consumption can be achieved by using modified climb procedures after an initial level altitude acceleration to an appropriate airspeed.
4. The use of modified climb procedures can be used to produce optimum fuel profiles when known ATC delays are forecast. Delays ranging from 0.5 to 1.0 minutes can be achieved with no fuel penalty through the use of the modified procedures.

5. For the heavy B737 aircraft, slightly greater cost benefits can be obtained through the use of modified climb procedures as compared to the standard procedures.
6. For the DC-10 aircraft a slight cost benefit can be achieved for all aircraft weights by using modified procedures. The benefit ranges from \$1.70 to \$5.20 per climb.
7. Accelerating modified climb procedures starting at 129 m/s (250 kt) at 3048 m (10,000 ft) with no level acceleration yield significant time, fuel and cost penalties relative to standard procedures.
8. The tradeoff between time and fuel benefits for descents is relatively linear, consequently, no optimum value exists.

The relationship for the time fuel ratio is:

B737

- 29,483 Kg (65,000 lbs) - 1 minute/50 Kg (110 lbs) of fuel
- 40,823 Kg (90,000 lbs) - 1 minute/52 Kg (115 lbs) of fuel

DC 10

- 108,862 Kg (240,000 lbs) - 1 minute/73 Kg (160 lbs) of fuel
- 163,293 Kg (360,000 lbs) - 1 minute/84 Kg (185 lbs) of fuel

9. Throttled, shallow gradient VNAV descents require more fuel than do conventional descents requiring the same amount of time to descend. Consequently, they appear to cause an economic penalty to the user.
10. The primary advantage of a VNAV descent relative to the standard or modified descent procedure is the positive identification of the start descent point. This descent procedure is less affected by wind effects insofar as distance traveled between altitude levels.
11. The higher speed descents exhibit a more cost effective descent characteristic since the aircraft time costs are greater than the fuel costs as compared to the ratio of time-fuel tradeoff values listed in paragraph 8.

## 6.1 TCV CURVED APPROACH IMPLEMENTATION

The intent of this section is to consider the requirements for implementing the curved approach capability into the avionic complement currently installed on the NASA TCV aircraft. Fortunately, the functional characteristics of the TCV Advance Guidance and Control System (AGCS) are sufficiently flexible and capable to render the aircraft amenable to curved approach applications [Reference 36]. The most significant feature accounting for the system's applicability is the closed-loop guidance function provided to execute the turn in anticipation of the transition from one flight segment to another. As the aircraft approaches the transition point, the AGCS computes the nominal bank angle required to accomplish the track angle change necessary to intercept the following path segment. The independent variable in the determination of the bank command is the desired radius of turn. In addition the AGCS derives:

- The center-of-turn vector used in computing the cross track deviation of the aircraft from the desired transition arc
- The desired track angle used in computing the aircraft heading error
- The points at which the transition arc is tangent to the inbound and outbound path segments to define the beginning and end of the turn maneuver

During the turn, the AGCS provides active guidance to maintain the continuously changing curved path. In many respects the AGCS turn guidance mode is functionally identical to the guidance concept discussed earlier. However, with respect to the definition of the nominal curved path, the AGCS is distinctly different. The parameters defining the curved path are implicitly specified by the turn radius and the three waypoints indicating the inbound and outbound path segments. The notation previously introduced, hereafter referred to as the arc segment notation, describes the curved path in terms of an initial waypoint and

the center of curvature. The two notations are compared in Figure 6.1. The conversion from the arc segment to AGCS notation is accomplished by first computing the turn radius

$$R_1 = |p_1 - c_1|$$

and the unit vector from  $c_1$  in the direction of  $q_2$

$$u_3 = (u_1 + u_2) / 2$$

The unit vectors  $u_1$  and  $u_2$  are defined by

$$u_1 = (p_1 - c_1) / R_1$$

$$u_2 = (p_2 - c_1) / R_1$$

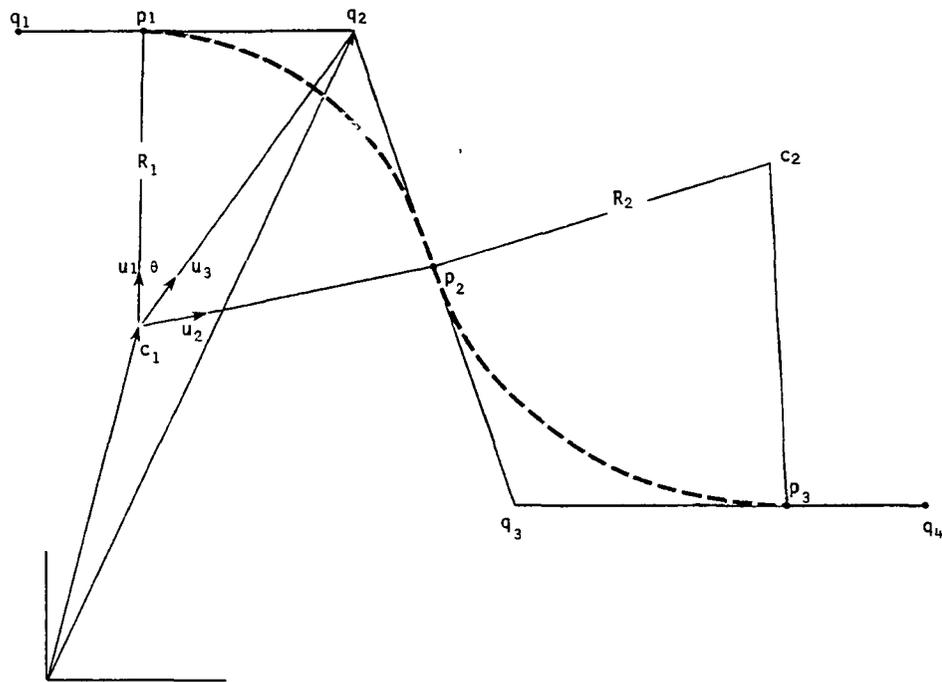
The magnitude of the vector  $(q_2 - c_1)$  is given by

$$R_1 / \cos\theta = R_1 / (u_1 \cdot u_3) = 2R_1 / (1 + u_1 \cdot u_2)$$

Thus the vector  $q_2$  is determined by

$$q_2 = c_1 + \left[ \frac{R_1}{1 + u_1 \cdot u_2} \right] [u_1 + u_2]$$

The vector  $q_3$  is computed from  $p_2$ ,  $p_3$ , and  $c_2$  in an identical manner. The vectors  $q_1$  and  $q_4$  are respectively determined by the characteristics of the path immediately preceding and succeeding the curve shown. Although the two notations describe the same curved path in space, there are minor differences involved in implementing the two approaches. The AGCS notation is more concise. To describe the path shown in Figure 6.1 requires the specification of fourteen parameters, three coordinates for each of the four waypoints plus two turn radii. For the same path the arc segment notation requires fifteen variables, three coordinates for each of the three waypoints and also for each of two centers of curvature. However, since the tangent points and the turn centers must be evaluated in the AGCS software to execute the curved segment, there is definitely a tradeoff between the path specification and guidance computation requirements. The tradeoff can only be examined by programming the two approaches on a specific guidance computer and comparing core storage and execution time requirements.



Arc Segment Notation  
 $p_1, p_2, p_3$  = Waypoints Along Curved Path  
 $c_1, c_2$  = Points Locating Centers of Curvature

AGCS Notation  
 $q_1, q_2, q_3, q_4$  = Waypoints Defining Arc Tangents  
 $R_1, R_2$  = Turn Radii

Figure 6.1 Curved Path Waypoint Notations

Another consideration is the fact that the waypoints at the turn in the AGCS notation ( $q_2$  and  $q_3$  in Figure 6.1 ) are actually "phantom" points in the sense that they do not coincide with the desired flight path. This characteristic might be objectionable in the interpretation of any graphic description of the curved profile, i.e., an approach plate. However, in the design of a real-time situation display, the difference would be inconsequential since the software driving the display could also be applied to derive the necessary references to indicate the desired path.

There is one minor difficulty to be considered in the utilization of the AGCS software to execute a curved approach involving two successive-arc segments. The system was designed to guide the aircraft along a sequence of straight-line segments connecting waypoints and also to provide guidance during the turn in anticipation of the leg-to-leg transition. The difficulty in executing consecutive turn segments stems from the fact that the computation of the parameter to cue the bank-to-turn maneuver is inhibited during the turn procedure. To demonstrate the effect of this turn procedure, consider the sequence of events encountered along the curved path in Figure 6.2 . As the aircraft approaches the waypoint  $q_2$  along the inbound segment ( $q_2 - q_1$ ), the incremental time to intercept the tangent point  $t_1$  is continuously computed on the basis of the groundspeed by

$$\Delta t = |p_1 - t_1| / V.$$

When  $\Delta t$  equals the time required to attain the nominal bank angle at the maximum roll rate, i.e., when

$$\Delta t = \phi_{\text{nom}} / \dot{\phi}_{\text{max}},$$

then the command to initiate the roll maneuver is issued to the flight control system. A similar procedure is employed to commence the roll out of the turn to a wings level altitude except that the turn angle accomplished,  $\theta$ , is monitored

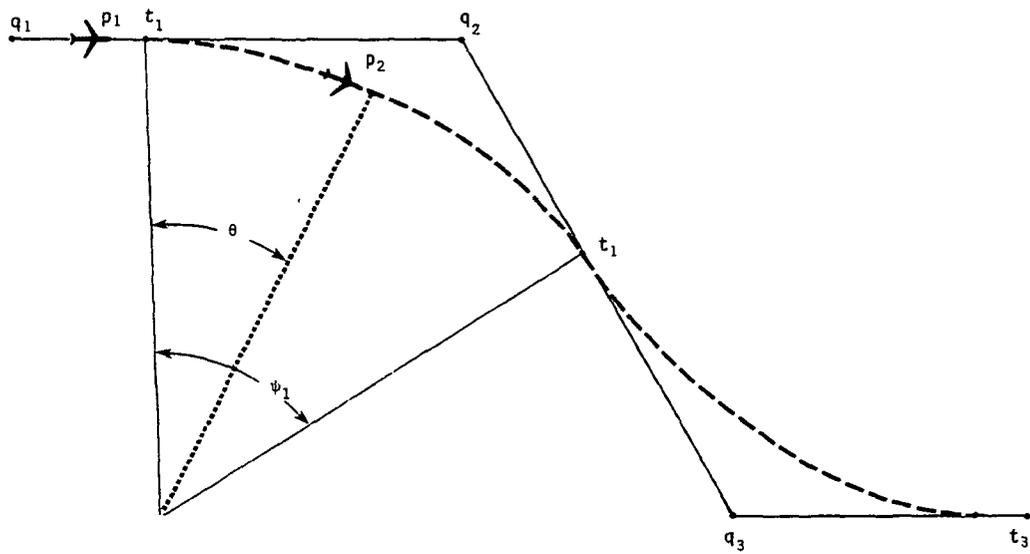


Figure 6.2 AGCS Waypoint Notation for Successive Arc Segments

instead of  $\Delta t$ . The roll out is initiated when

$$(\psi - \theta) = (\phi_{\text{nom}} / \dot{\phi}_{\text{max}}) V/g$$

During the turn maneuver,  $\Delta t$  is not computed since the design was based on the assumption that a linear segment would follow the turn. Thus, for the curved path shown in Figure 6.2, no bank angle command to assume the following arc segment would be issued immediately after the turn procedure is completed. Instead the aircraft would continue along the linear segment tangent to the arc at  $t_1$  until the AGCS sensed the condition indicative of an imminent turn to intercept the following track. No assessment was made of the impact of the turn anticipation logic on the precision of executing two successive arc segments since this would have involved the exact duplication of the AGCS logic and event sequencing. Thus it is recommended that the procedure be investigated further using the AGCS software simulator.

## 6.2 MLS DERIVED HEADING

To achieve a high precision in following a specified ground track, an accurate measurement of the orientation of the aircraft velocity vector is necessary to enable the guidance system to compensate for the lateral-axis component of the wind. In aircraft equipped with an inertial reference system the vector orientation is obtained directly from the sensed inertial velocity components. However, very few aircraft are so equipped and thus the measured aircraft heading is used to approximate the velocity heading in the guidance control law or an estimated correction is applied to compensate for the wind direction. In the future terminal area environment, where MLS would provide an accurate position location with respect to an inertially fixed reference frame, the velocity heading of an aircraft on approach could be derived from this signal source. The obvious approach to obtain the velocity vector orientation from MLS measurements would be to difference successive position coordinates derived from indicated range, azimuth, and elevation. However, this approach would necessitate filtering to minimize the noise content since the differential

process naturally tends to accentuate the high frequency noise components present in the MLS signal. An alternative approach was suggested by a review of literature relating to the application of nonlinear filtering techniques to re-entry vehicle tracking [References 37, 38, 39, and 40] and orbit determination [References 41 and 42]. The estimation of the position of a re-entry body from tracking radar measurements is analogous to the problem of determining the position of an approaching aircraft from MLS measurements. Thus the techniques proposed were applied to determine the velocity heading. However, some simplifying assumptions were made about the aircraft's motion in order to reduce the number of states included in the filter design. The assumptions involved the following conditions:

- The rate of change of groundspeed is negligible compared to the heading rate-of-change. Thus the parameter can be eliminated as a state and either derived from independent measurements or estimated in an "outer loop" at a slower sampling rate.
- The heading rate is constant along a given arc segment.

If these assumptions prove to be invalid, then the filter could be augmented to include the velocity and heading rate states. Also, to simplify the design, motion was confined to a plane, i.e., no consideration was given to the effect of elevation measurements. The latter assumption is probably most restrictive since it renders the design impractical in a realistic application. However, the intent of the exercise was to examine the feasibility of the approach rather than specify a final design. Under these conditions, the following nonlinear difference equations are descriptive of the aircraft motion along a curved path:

$$r_k = [r_{k-1}^2 \delta + 2r_{k-1} \delta \cos(\psi_{k-1} - \theta_{k-1})]^{1/2} \quad (6.1)$$

$$\theta_k = \theta_{k-1} + \tan^{-1} [(\delta \sin(\psi_{k-1} - \theta_{k-1})) / (r_{k-1} + \delta \cos(\psi_{k-1} - \theta_{k-1}))]$$

$$\psi_k = \psi_{k-1} + \phi$$

where  $r_k$ ,  $\theta_k$ ,  $\psi_k$  are the range, azimuth, and velocity heading at time  $t = t_k$  (Figure 6.3) and

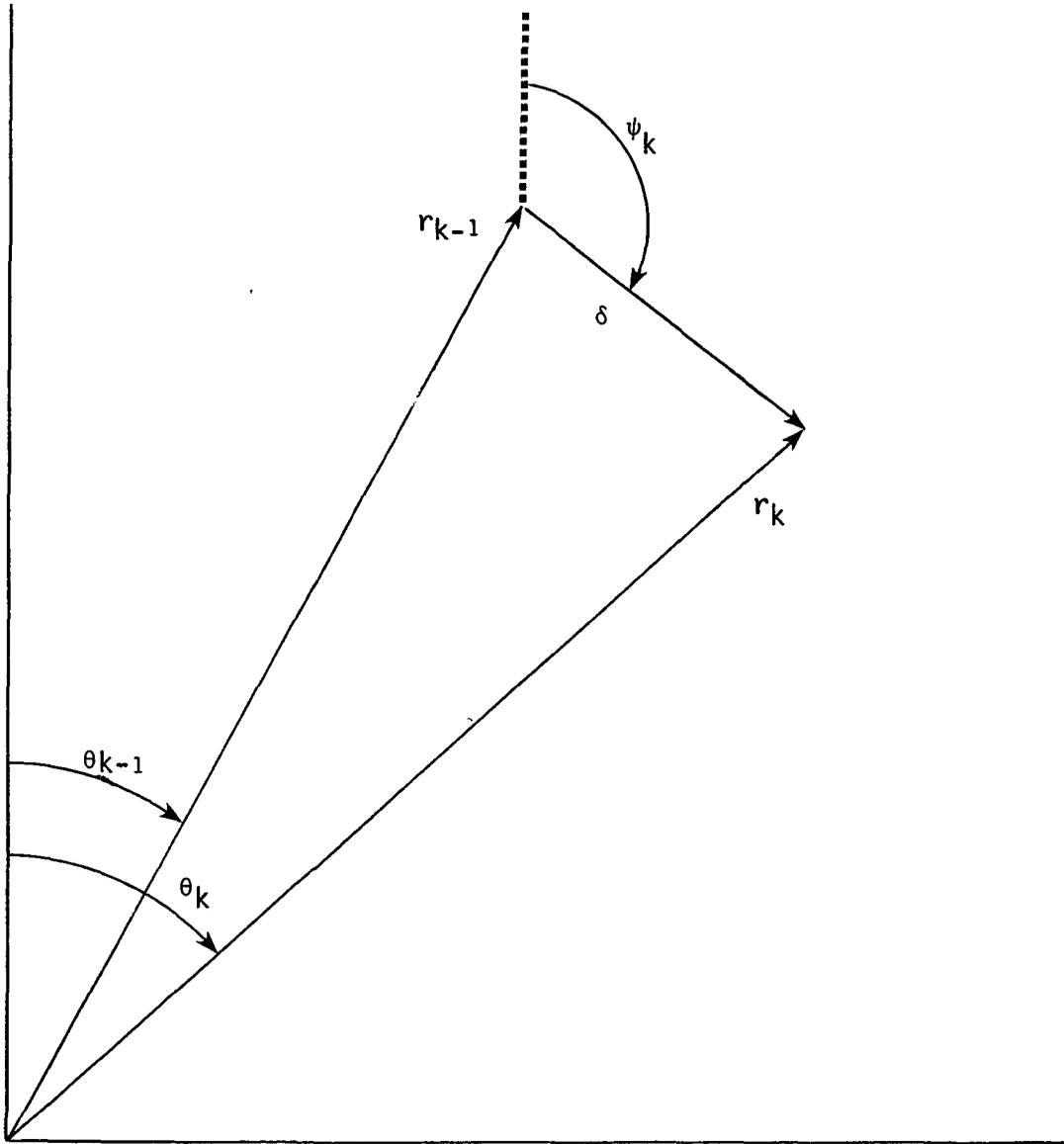


Figure 6.3 MLS Tracking Geometry

$$\delta = V\Delta t$$

$$\phi = \dot{\psi} \Delta t.$$

Since the range and azimuth are the direct outputs of an MLS receiver, these parameters were selected as the filter states so that the measurement equation would be linear. However, the transformation from the MLS spherical coordinate system to the Euclidean reference frame is unavoidably nonlinear, thus the nonlinear system equations must be accepted. With a nonlinear system a truly optimal filter is physically unrealizable, since its implementation would require an infinite number of states. Thus an approximation to the optimal nonlinear filter is required.

In the discrete linear case where the system dynamics are defined by the linear matrix difference equation

$$x_k = A_k x_{k-1} \quad (6.2)$$

and the noisy measurements are related to the states by

$$y_k = H_k x_k + \xi_k \quad (6.3)$$

where  $\xi_k$  is determined by a Gaussian white-noise process, and

$$E[\xi_k, \xi_k] = R_k$$

then the minimum variance estimate of the state,  $\hat{x}_k$ , from a given measurement  $y_k$  is determined by

$$\hat{x}_k = \hat{x}_{k, k-1} + W_k (y_k - H_k \hat{x}_{k, k-1}) \quad (6.4)$$

where

$$\hat{x}_{k, k-1} = A_k \hat{x}_{k-1} \quad (6.5)$$

$$W_k = S_{k, k-1} H_k^{-1} (R_k + H_k S_{k, k-1} H_k^{-1})^{-1} \quad (6.6)$$

$$S_{k, k-1} = A_k S_{k-1} A_k^{-1} \quad (6.7)$$

$$S_k = S_{k-1} - W_k H_k S_{k-1} \quad (6.8)$$

The matrix  $S_k$  is the covariance of the error in the current estimate, i.e.,

$$S_k = E [(x_k - \hat{x}_k) (x_k - \hat{x}_k)^T].$$

In the nonlinear case where (6.2) no longer applies and the evolution of the state is determined by a nonlinear difference equation

$$x_k = f(x_{k-1}), \quad (6.9)$$

a suboptimal filter can be derived by expanding the state equation (6.9) in a Taylor series about the previous estimate  $\hat{x}_{k-1}$ . If only first-order terms are considered [Reference 37], then the expansion results in the following difference equation

$$x_k - f(\hat{x}_{k-1}) = A_k (x_{k-1} - \hat{x}_{k-1}) \quad (6.10)$$

where  $A_k$  is the Jacobian matrix of  $f(\hat{x}_{k-1})$  with elements

$$[A_k]_{ij} = \left. \frac{\partial f_i}{\partial x_j} \right|_{x=\hat{x}_{k-1}} \quad (6.11)$$

Recognizing that  $\hat{x}_{k, k-1} = f(\hat{x}_{k-1})$  and substituting (6.10) in the expression for the a priori covariance matrix

$$S_{k, k-1} = E[(x_k - \hat{x}_{k, k-1}) (x_k - \hat{x}_{k, k-1})^T]$$

yields

$$\begin{aligned} S_{k, k-1} &= E[A_k (x_{k-1} - \hat{x}_{k-1}) (x_{k-1} - \hat{x}_{k-1})^T A_k^T] \\ &= A_k S_{k-1} A_k^T. \end{aligned}$$

Thus, except for (6.5), the recursive estimation equations, (6.4) thru (6.8), approximate the optimal nonlinear filter when  $A_k$  is the Jacobian matrix defined by (6.11). The propagation of the state estimate is achieved by

$$\hat{x}_{k, k-1} = f(\hat{x}_{k-1}). \quad (6.12)$$

The elements of the Jacobian matrix were derived for the velocity heading application by differentiating the state equations (6.1) and are shown in Table 6.1 .

$\begin{matrix} j \\ i \end{matrix}$	1	2	3
1	$(r_{k-1} + \delta c_{k-1})/r_k$	$\delta r_{k-1} s_{k-1} / r_k$	$-A_{12}$
2	$-\delta s_{k-1}/r_k^2$	$1 - (\delta r_{k-1} c_{k-1} + \delta^2)/r_k^2$	$1 - A_{22}$
3	0	0	1

$$c_k = \cos (\psi_k - \theta_k)$$

$$s_k = \sin (\psi_k - \theta_k)$$

Table 6.1 Jacobian Matrix Elements

The preceding technique was applied to estimate the velocity vector heading along the arc segment approach to Washington National. The error in both the measurements of range and azimuth was modeled as an additive Gaussian white noise with zero mean and standard deviations given by:

$$\sigma_R = 100 \text{ ft.}$$

$$\sigma_\theta = 0.1 \text{ deg.}$$

The initial errors in the estimate were assumed to be uncorrelated and the diagonal elements of the covariance matrix were assigned the values

$$S_{11} = \sigma_R^2$$

$$S_{22} = \sigma_\theta^2$$

$$S_{33} = (2 \text{ deg.})^2$$

This simulation exercise demonstrated that the suboptimal estimator could follow the velocity vector heading along the continuously changing curved path with a reasonable accuracy. With the exception of the estimates immediately following a segment transition, the estimated velocity heading was within 2 degrees of the true velocity vector orientation. The r.m.s. error in the velocity heading estimate along the complete path was less than 2.5 degrees. Following the transition the error was significantly greater due to the fact that the model assumes a constant heading rate, when actually the rate is changing to accomplish the transition in the bank angle. The most noticeable error occurred at the transition from a linear segment to an arc segment. Apparently, during this phase, the filter is able to catch up with the dynamic process and improve its estimate of the state. This effect was evident as a significant decrease of the r.m.s. error in the estimate of velocity heading. Thus the impact of the modeling error is emphasized as the measurement residuals are more heavily weighted due to the decrease in the error covariance. Also, during the linear segment, a constant offset in the velocity heading estimate was noted. This observation led to the consideration of a second-order approximation to the optimal estimator.

The development of a second-order filter to estimate the state of a nonlinear system from noisy measurements was motivated by the observation that, for the extended Kalman filter described above, the deviations between the true and estimated states were greater than the errors predicted by the calculated covariance matrix [Reference 38]. The approximate filter was derived by introducing a bias correction term in the propagation of the estimate between measurements. Thus (6.12) is modified and described by

$$\hat{x}_{k, k-1} = f(\hat{x}_{k-1}) + \mu_k \quad (6.13)$$

where  $\mu_k$  is determined by the requirement that, at each stage of the iteration, the a priori estimate is unbiased, i.e.,

$$E [x - \hat{x}_{k, k-1}] = 0$$

For the velocity vector heading application, this condition is satisfied by

$$\mu_1 = \frac{1}{2} \text{tr} [B_{1k} S_{k, k-1}]$$

$$\mu_2 = \frac{1}{2} \text{tr} [B_{2k} S_{k, k-1}]$$

$$\mu_3 = 0$$

where  $B_{ik}$  is the symmetric Hessian matrix involving the second partials of  $f_i(\hat{x}_{k, k-1})$ , i.e.

$$[B_{ik}]_{mn} = \left. \frac{\partial^2 f_i}{\partial x_m \partial x_n} \right|_{x=\hat{x}_{k, k-1}}$$

Thus the recursive equations for the second-order filter are identical to those for the first-order (extended Kalman) filter except that the bias correction term is applied to update the estimate prior to a new measurement.

The second-order filtering technique was applied to the estimation of velocity vector heading from MLS range and azimuth observations. The initial conditions and noise process descriptions were assumed identical to those of the preceding simulation experiment. The exercise demonstrated a measurable improvement in the estimate of velocity heading. The most notable difference was observed along the linear track segment where the error at the conclusion of the segment was reduced by an order of magnitude. However, the transient effect at the beginning of the track still persisted so that the net effect was a reduction in the r.m.s. error along the linear segment from .88 degrees for the first-order filter to .77 degrees for the second-order filter. The total r.m.s. error for the entire approach was reduced to 2.15 degrees.

Without question, the above simulation experiments are not sufficient to conclude that the concept should be considered for immediate implementation as the means to derive the velocity vector orientation from MLS measurement data. The assumption that the velocity and heading rate are both constant along a given segment is probably too restrictive. The impact of the constant rate assumption noticeably affected the accuracy of the velocity heading estimate following the transition from one segment to another. The transient effect of a bank angle change is noticed as an increase in the estimation error due to the fact that the model is an inaccurate representation of the dynamics. Further refinement of the model should be considered. Also, consideration should be given to the relative advantage of the second-order filter vs. the first-order filter. Although the simulations demonstrated an increased accuracy for the higher order approximation, it is doubtful that this small improvement warrants the additional complexity. Further the simulation tests only reflect the results for a single case. It is very likely that the filter performance is strongly path dependent. However, the analysis does indicate that the approach is feasible. The 2.5 degree accuracy obtained is considerably better than that to be expected from a heading reference and an estimate of the wind, especially along a curved approach where the orientation of wind velocity vector is continuously changing with respect to the aircraft heading.

### 6.3 VERTICAL PATH CONTROL

The incorporation of the vertical control modes described in Section 4.3 into actual aircraft operations will require that some modifications be made to most aircraft that are in use in the civil fleet at the present time. For test and evaluation purposes, however, these control modes should be easily adapted to the TCV aircraft. In the following paragraphs a description of the general vertical control system design will be discussed along with the specific application to the TCV aircraft.

The two primary controls which influence the vertical flight path of any fixed-wing aircraft are the propulsion system controls and the elevator deflection. Through these two controls the pilot or autopilot system manages all of the parameters associated with vertical flight. These parameters include:

- Speed
- Altitude
- Rate of Climb
- Angle of Attack
- Flight Deck Angle
- Flight Path Angle

These six parameters are used to provide information to the pilot to indicate the status of the aircraft in the vertical dimension. The first five parameters are directly observable by aircraft sensors and instruments. Flight path angle is a linear combination of angle of attack and flight deck angle. These sensor inputs are processed by the pilot or the automatic flight control system (AFCS) from which the necessary changes in elevator or throttle are determined. The control inputs are sent to the particular control actuators which in turn produce a change in the engine power level or a deflection in the elevator surface. The loop is closed as the aircraft responds to the control inputs and the sensors record the change

for input to the pilot or the AFCS. The topics that will be discussed throughout the rest of this section relate to how the sensor information can be processed and used by the pilot or the AFCS to produce the desired aircraft vertical profiles.

### 6.3.1 Control Mode Implementation

Several of the profiles that have been described in this report utilize the aircraft speed as the governing factor in controlling the vertical flight path. In these cases a command speed can be developed by sensing the aircraft altitude and processing the altitude data to produce command speed through pilot-selectable profile control inputs. The functional relationship can be expressed as follows:

$$V_C = f(h)$$

where  $V_C$  = command speed  
f = functional relationship  
h = aircraft altitude

The command speed may be expressed as an indicated airspeed or a Mach number. The speed error can be computed by comparing the command speed to the appropriate quantity from the air data computer. The error signal can be used to determine the changes required in the elevators or the engine power. A generalized block diagram of the entire control process is shown in Figure 6.4.

In addition to command speed, the flight path angle must be used to determine some of the control inputs for certain control modes. In this case the parameter that is being controlled, the flight path angle, can be related to the aircraft altitude. Through inputs to the control display unit, the vertical path is defined. Through inputs from the navigation system, the aircraft position is known and the command altitude can be generated. Comparison with actual altitude produces the altitude error which can be then displayed to the pilot or the AFCS. VNAV path control is discussed in Reference 29 and the following

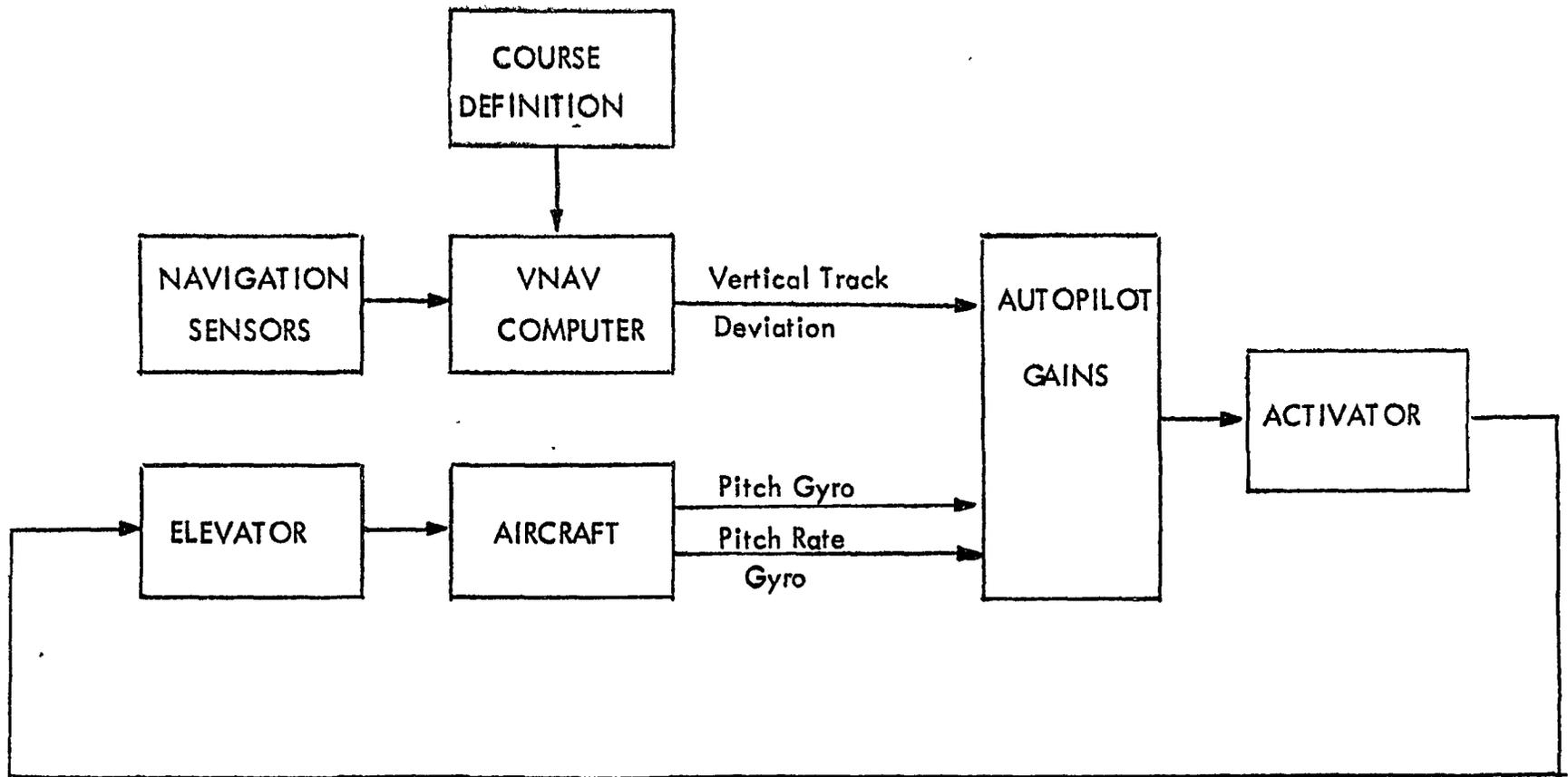


Figure 6.4 Vertical Control System

generalized diagram, Figure 6.5, shows the control signal processing that is performed in VNAV flight. In the remaining control modes a combination of VNAV control and command speed control is necessary. A summary of the control modes used in the study and the type of aircraft control required is as follows:

1. Constant flight path angle - VNAV mode
2. Constant  $d(V_I)/dH$  - command speed mode
3. Constant  $d(\text{Mach})/dH$  - Command speed mode
4. Constant  $V_I$ , constant flight path angle - VNAV and command speed mode
5. Constant Mach, constant flight path angle - VNAV and command speed mode
6. Constant rate of climb - Existing flight mode

A mode select control and logic will be required to operate the aircraft in the various flight situations. In addition control limiters will be required to keep the aircraft within the operational flight envelope defined by safety and airframe structural constraints. The specific description of each control system design is dependent upon the characteristics of individual aircraft types and is a subject which requires further investigation before it can be implemented.

### 6.3.2 TCV Implementation

The special aircraft instrumentation that is contained on the TCV aircraft makes this aircraft quite suitable for testing and evaluating the various flight procedures described in this report. The aircraft has existing VNAV and auto-throttle systems which will considerably simplify the design of the flight control system. The major items that need to be considered for this aircraft are:

1. Mode select control and logic
2. Speed vs altitude functional description
3. Control display unit for profile controller
4. VNAV and autothrottle control compatibility

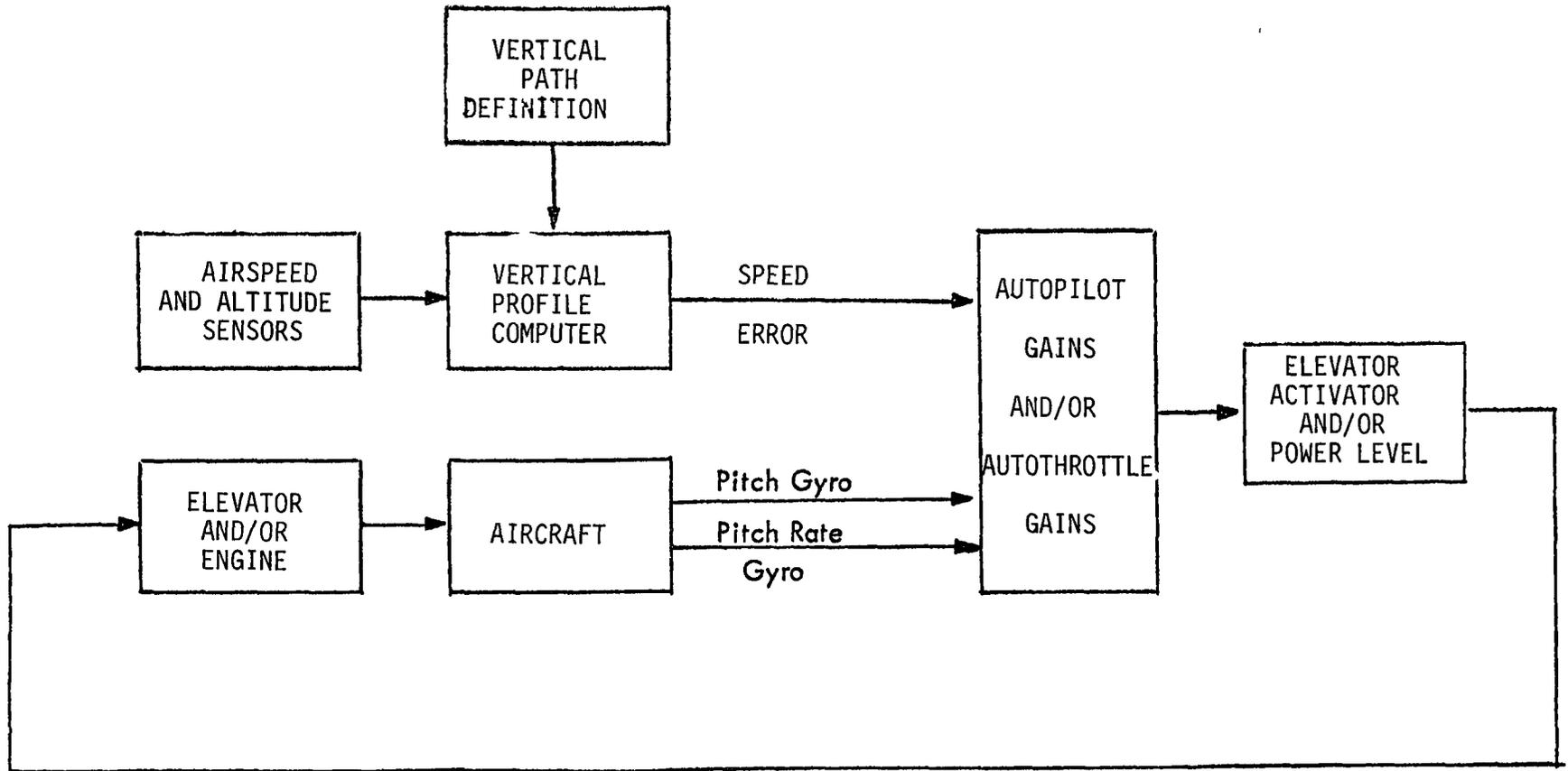


Figure 6.5 Vertical Control System for Modified Flight Path Control

The mode selector must be capable of providing the connections between the appropriate components of the navigation, air data, AFCS, autothrottle and flight instrument systems that will make the aircraft follow the desired profile. Such a mode selector could be a multiposition switch or a digital processor to control the digital flight computer.

The speed vs altitude functional description creates the command velocity from inputs of altitude from the altimeter and profile descriptions from the speed vs altitude profile controller. This unit should be capable of storing one or more profile segments and the parameter that indicates when that segment has been completed. It is also desirable to have the unit be capable of sequencing between segments or alerting the pilot as to when a profile change is about to occur. It is quite possible that the speed vs altitude functional description and the control display unit for the profile controller could be incorporated into the C-4000 digital computer unit onboard the TCV aircraft. It may be possible to incorporate some of the mode selection logic in the same unit.

The compatibility and logic required for operating the aircraft in the selected control modes with both VNAV and/or autothrottle engaged must be analyzed thoroughly in order to preclude the possibility of entering undesirable flight conditions. Limits to critical parameters such as speed, angle of attack, rate of descent, etc., must be established and appropriate hardware and software system designs to incorporate this logic must be included in the aircraft control system.

#### ~~6.4~~ SUMMARY OF SECTION 6

The waypoint notation previously introduced to describe an arc segment was modified to accommodate the characteristics of the Advanced Guidance and Control System (AGCS) of the TCV aircraft. The resulting notation is considerably more concise but probably less descriptive of the desired flight path. Also, one

possible modification of the AGCS software required to execute the arc segment approach involves the logic to initiate the bank maneuver in anticipation of a curved segment. It is possible that this function would hinder the transition from one arc segment to another. The assessment of the impact of the currently programmed turn anticipation logic can only be gained from a detailed simulation of the software and aircraft systems.

An analysis was performed to evaluate the feasibility of deriving the orientation of the velocity vector from MLS measurement data. A very basic model approximating the relationship between range, azimuth, and velocity vector heading was developed and utilized in an algorithm to estimate these parameters from MLS measurements. Since the state equations describing the dynamic process are nonlinear, an approximation to the optimal estimator was required. Both first and second order approximate forms were considered. The resulting algorithms were applied to estimate velocity vector heading along the arc segment approach to runway 18 at Washington National. The experiment demonstrated that the filter could track the velocity vector heading with reasonable accuracy; however, abrupt deviations in the estimates were observed following track changes. This effect is most likely due to approximations made in the development of the process model. Further refinement of this model is required.

The incorporation of the control mode structure to provide the vertical profiles that were described in this report requires the use of instrumentation that is not presently available in most aircraft. In order to incorporate these functions for manual flight control a profile generation control display unit and a VNAV computer would be necessary. The pilot would select the desired profile by making entries into the control unit. Command speed and/or altitude would be computed by the unit and the pilot would receive visual

indications of speed and/or altitude error depending on the selected control mode. In order to implement an automatic version of the vertical path controller the profile control unit would be used in conjunction with an autothrottle as well as the VNAV computer. This type of installation would require the use of some amount of software logic to be used in conjunction with the AFCS to prevent the aircraft from entering undesirable flight conditions.

## 7.0

## CANDIDATE FLIGHT TESTS

### 7.1 SIMULATE DCA CURVED APPROACH AT NAFEC

As indicated previously, the installation of an MLS facility at Washington National Airport (DCA) to enable guidance along curved approach paths would substantially benefit operations in at least two respects: increased airport utilization and decreased noise exposure.

The approach to runway 18 at DCA is complicated by several factors. The restricted zones to the north of the airport prohibit the preferred straight-in approach along the extended runway centerline from the outer marker to the threshold. Thus an ILS localizer beam aligned with the runway would be useless. Furthermore, elevated structures in the vicinity of the airport dictate that both lateral and vertical precise path control be exercised to avoid catastrophic encounters. Under favorable conditions the preferred approach is to utilize the Potomac River as a visual reference. When the weather deteriorates to the point where the visual procedure is inappropriate, an instrument approach from the northwest is possible, though less desirable from the standpoint of noise exposure and obstacle avoidance. However, the necessary turn to align the flight path with the runway dictates that a visual reference be acquired prior to this maneuver since the existing landing aids fail to provide the guidance required to execute the turn. Thus the established minima are relatively high [1.85 Km (1.1nm) and 219 m (720 ft)]. An MLS installation providing continuous guidance on approach would reduce the minima to at least the limits of Category II. The implementation of MLS would thus permit approaches to runway 18 under less favorable weather conditions, and consequently increase the overall airport utilization. However, this assertion is predicated on the demonstration that the final turn can be accomplished using MLS guidance without compromising safety.

The noise impact is also a significant factor at Washington National, where densely populated areas surround the airport. Minimum noise exposure is realized with the visual approach procedure since the maximum noise concentration is over the Potomac River. MLS guidance could be utilized to approximate the same approach path and thus realize the same low noise exposure when conditions prohibit visual procedures. The issues affecting the application of MLS to this advantage include the consideration of the final approach maneuver sequence indicated above as well as the degree of accuracy required of the guidance system to insure that the ground track is within the bounds of the noise insensitive region. The required accuracy to achieve an effective noise abatement approach to runway 18 at Washington National is 185 m (0.1 nm).

#### 7.1.1 Test Objectives

To determine whether the curved approach to runway 18 at Washington National is a practical application of MLS, it is recommended that an analog of the approach be conducted in a flight experiment at the National Aviation Facilities Experimental Center (NAFEC) where a demonstration MLS facility is located. The intended objectives of the proposed flight test are two fold:

- To investigate the operational implications of a curved final approach segment.
- To evaluate the degree of precision attainable with MLS guidance along an arc segment approach.

The curved segment approach to runway 18 at DCA should serve as a reasonable test case. The constraints imposed on the approach to this runway due to both topographic and demographic considerations are no doubt unique to the Washington terminal area and thus it might be argued that the results might only be of regional significance. However, this exercise should also be considered to represent a worst case example since the guidance and control re-

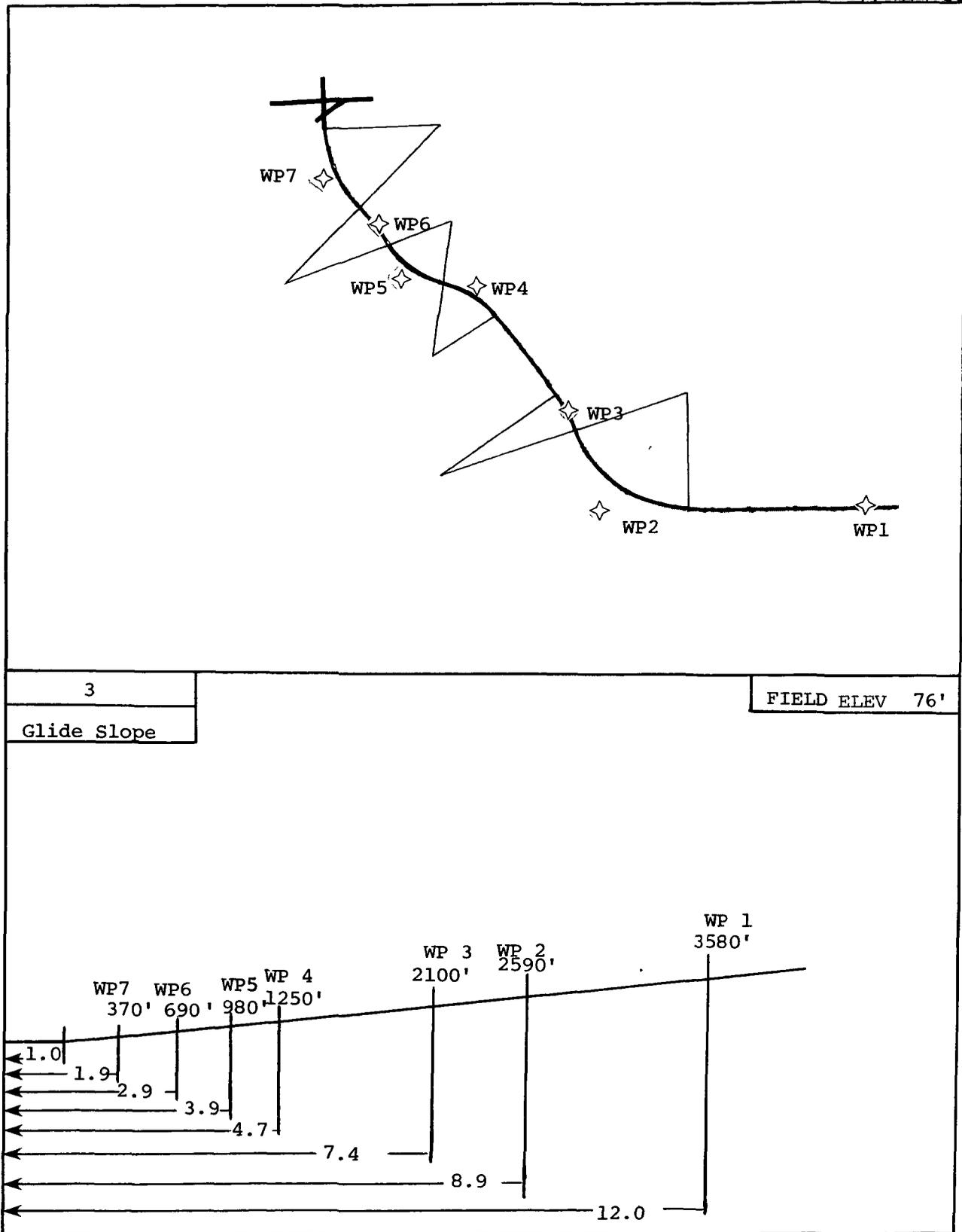
quirements necessary to execute the sequence of curved segments are probably more severe than those for any other current approach procedure. Therefore, should the curved approach to Washington National prove to be practical, it is then very likely that these results will inspire consideration of other applications.

#### 7.1.2 Test Plan

The horizontal and vertical profiles for this flight test are illustrated in Figure 7.1. The horizontal profile is identical to the visual approach path to runway 18 at Washington National except that it has been rotated 140 deg. to enable utilization of the MLS facility on runway 04 at NAFEC. The waypoints shown are consistent with the notation of the AGCS on the TCV aircraft.

The approach begins at WP1, 22 Km (12 nm) from the DME on runway 4 and at an altitude of 1091 m (3,580 ft). The vertical profile is a constant 3° glide-slope beginning at WP1. In Figure 7.1, the altitude designations at those waypoints which are not coincident with the flight path are actually the levels that are encountered at the point of closest approach, i.e., along the angle bisector. At 18.5 Km (10 nm) the aircraft executes a gradual turn [1 deg/s at 62 m/s (120 Kt)] and assumes this track for about 75 sec. Following this segment is a shorter (22 sec) and more gradual turn in the opposite direction to intercept the linear segment 13 Km (7 nm) from the DME site. After 52 sec of flight along the linear segment, the aircraft encounters a sequence of higher rate turn maneuvers (1.6 and 1.8 deg/s), each lasting about 35 sec. The final sequence consists of two 1 deg/s arcs, the last of which begins at 4.6 Km (2.5 nm) from the DME site and, after 45 sec of flight, concludes in touchdown on runway 4 at NAFEC.

The series of tests considered appropriate to evaluate the curved approach procedure include:



MLS Rwy 4

Atlantic City, New Jersey  
NAFEC Atlantic City

Figure 7.1 Arc Segment Approach Profile

- A. Manual flight control-execute missed approach at 61 m (200 ft)
- B. Manual horizontal path control-automatic vertical control-execute missed approach at 61 m (200 ft)
- C. Automatic 3D flight control-execute missed approach at 61 m (200 ft)
- D. Manual flight control-approach and land
- E. Automatic 3D flight control-approach and land

This series was considered as a gradual phase-in of both the automatic flight control function and the critical landing phase. The intent of this progression was to first familiarize the flight crew with the maneuvers involved in executing the curved approach profile. Then in the later stages of the flight test, when the control function is assumed by the automatic landing guidance system, the crew would be able to recognize and respond to unusual situations. Also, in the initial phase of the series, the intent is to anticipate the effect of the final arc segment on landing system performance without jeopardizing safety. Thus the missed approach procedure involves a leveling at 61 m (200 ft.) and a continuation of the horizontal path guidance. With this procedure it is possible to experience the lateral maneuvers to align the final approach path with the runway independent of the maneuver sequence required to achieve touchdown. The conditions observed over the threshold at 61 m (200 ft) would then be indicative of the situation expected at touchdown.

The preceding series of tests are primarily intended to assess the response of the guidance system and the reactions of the flight crew to the curved approach procedure. However, as indicated earlier in Section 5.1, other factors of significance include the effect of groundspeed variations on the achieved track and the measurement of heading applied to the guidance control law. The groundspeed effect is realized through the computation of bank angle command to accomplish the desired turn. If the bank command is computed continuously as a function of groundspeed, the effect is minimal. However, if the command is computed at the

commencement of the turn maneuver and held constant through the turn, then changes in the groundspeed will impact the flight trajectory. Since it is understood that the turn anticipation logic in the AGCS functions in the latter manner, it would be appropriate to consider the possibility of modifying this logic and examining the impact on the track achieved. Also, if aircraft heading, rather than inertial velocity heading, is applied to the control law, the track will deviate from the desired path. Thus, it is suggested that the following additional experiments be considered.

- F. Automatic 3D flight control-execute missed approach at 61 m (200 ft)-  
correct bank command to account for groundspeed variations
- G. Automatic 3D flight control - execute missed approach at 61 m (200 ft)-  
apply aircraft heading sensor to derive guidance commands
- H. Automatic 3D flight control - execute missed approach at 61 m (200 ft)-  
apply MLS-derived heading to evaluate guidance commands

In the latter case it was assumed that excess core storage would be available to implement either a smoothed differential position algorithm or a nonlinear filter based on the concepts discussed in Section 6.2.

The flight test plan indicated above is summarized in Table 7.1, where the relevant test conditions are indicated for each series in the sequence. The column labeled Bank Command refers to the frequency at which the bank angle command is computed during each arc segment. The Discrete designation implies that the command signal is evaluated once per segment at the initial point and held constant throughout the segment. The continuous mode relates to the case where the bank command is reevaluated at every computation cycle on the basis of the current measured groundspeed. The indicated number of flights per series was based on the supposition that a minimum sample size of 12 is desirable to gain reasonable statistical significance (Reference 43). Thus, for test series where performance factors are significant, 12 flights are preferred. Test series

Table 7.1 DCA Curved Approach Test Plan Summary

TEST SERIES	HORIZONTAL CONTROL MODE	VERTICAL CONTROL MODE	HEADING REFERENCE	BANK COMMAND	FLIGHT CONCLUSION	NO. OF FLIGHTS	FLIGHT HOURS
A	Manual	Manual	INS	Discrete	Missed Approach	6	2
B	Manual	Auto	INS	Discrete	Missed Approach	3	1
C	Auto	Auto	INS	Discrete	Missed Approach	6	2
D	Manual	Manual	INS	Discrete	Land	12	4
E	Auto	Auto	INS	Discrete	Land	12	4
F	Auto	Auto	INS	Continuous	Missed Approach	3	1
G	Auto	Auto	Magnetic Heading MLS Derived	Discrete	Missed Approach	3	1
H	Auto	Auto		Discrete	Missed Approach	3	1
TOTALS						48	16

D and E were considered in this category since they reflect the degree of precision expected for the complete curved approach with both manual and automatic flight control. Six missed approaches for series A and C were considered appropriate to gain a reasonable assessment of the conditions to be expected under actual landing conditions. Since series B represents a transition from the manual to automatic test phases, three flights were considered adequate. Also, for each of the other three test series, three approaches were judged to be a reasonable number of flights to acquire sufficient experience and test data to gain a preliminary assessment of the factors involved. The estimate of flight test hours was based on the assumption that three approaches per hour could be conducted without undue difficulty. The total plan is only intended to represent a preliminary indication of the tasks and level of effort involved in evaluating the curved approach procedures.

### 7.1.3 Data Requirements

The following general categories of information were considered appropriate to achieve the flight test objectives identified earlier.

- Flight Path Integrity

To determine the degree of precision achieved in executing the curved approach path, it is necessary to record actual aircraft position coordinates and velocity components as a function of time.

- Pilot Workload

To determine the level of effort required of the pilot to maintain the desired track in the manual flight mode, it is advisable to sense and record the throttle, control yoke, and elevator trim settings as a function of time. Also, to gauge the response of the pilot, it would be appropriate to record those parameters related to flight director commands and compare these with the recorded measurements of control actuator motions.

- Flight Crew Reactions

Since the curved approach to Washington National is in current practice under visual flight conditions, it is not expected that this flight test would stimulate any adverse reaction to the aircraft accelerations and attitudes experienced during approach. However, since the automatic flight control system might exhibit some unexpected response characteristics, it would be well to note the subjective reactions of the flight crew to uncomfortable situations.

- Controller Response

Since ATC controller surveillance is required to insure that the approaching aircraft do not significantly deviate from the intended track, it is important to consider his reaction to the curved approach procedure. Current controller displays are not easily adapted to enable a graphic presentation of the nominal approach path. Consequently, the dominant consideration in this information category should be an assessment of the controller's requirements for display of the desired track.

For those data items requiring a subjective evaluation, it is anticipated that a questionnaire would be prepared and submitted to the flight crew and controller participating in the flight test. The flight crew should be requested to:

- Evaluate the curved approach procedure in general
- Consider difficulties encountered in executing the procedure
- Evaluate pilot workload with regard to efforts required in other approach procedures
- Consider requirements for additional instrumentation

- Evaluate the procedure from the standpoint of safety

The controller questionnaire should reflect his reaction to the following issues:

- Difficulty of maintaining surveillance along curved approach path
- Additional display requirements to depict intended track
- Procedures to facilitate controller functions

Since the principal objective is to determine the degree of precision achieved in executing the curved approach profile, the measurement of deviation from the desired track as derived from repeated measurements of actual aircraft position is paramount. Also, since the guidance system's primary source of position information on approach is MLS, the data source utilized to gauge the accuracy of the aircraft system must be more precise than MLS. Considering both the onboard systems of the TCV aircraft and the ground facilities at NAFEC, there are several candidate position reference systems available for this purpose. These systems include:

- The inertial navigation system onboard the TCV
- The precision tracking radar of the EAIR facility at NAFEC
- The phototheodolite range at NAFEC

The INS provides a very precise indication of position and velocity components with only short term stability. In the long term, the errors due to instrument bias and drift effects tend to accumulate and corrupt the position and velocity measurements derived from the velocity and attitude increments. However, since the duration of the approach should never exceed 10 min., the effect of the drift components need not be regarded and only the bias terms require consideration.

The position measurements derived from phototheodolite sightings are considerably more precise than those obtained from inertial or radar measurements.

However, the procedures involved in continuously tracking the approaching aircraft and reducing the resulting data are very tedious. Thus continuous tracking should be avoided if possible. A more reasonable procedure would be to locate the aircraft precisely with the phototheodolite network at one point only on every approach and utilize this information to calibrate the INS errors.

The EAIR facility at NAFEC provides continuous tracking of an aircraft on approach with a degree of precision considerably better than that anticipated for MLS [18 m (60 ft) in range and .01 deg in azimuth and elevation]. Below a 3 deg elevation angle, distant radar measurements are not considered reliable; however, this restriction does not apply to measurements in the immediate vicinity of the antenna site and thus continuous radar coverage is provided down to the threshold. Also, the tracking accuracies encountered in previous flight tests involving the EAIR were observed to be both sight and distance dependent. Thus, to improve the overall tracking accuracy, tracking radar measurements complemented with INS measurement data should be considered as a possible data reduction procedure.

Other significant data items in addition to measured aircraft position and velocity are the aircraft magnetic and inertial velocity headings. This information would be required in the comparative evaluation of the different sources of heading reference applied to the guidance control law. Also, the information would be useful in estimating the local wind and the response of the guidance system to wind variations.

#### 7.1.4 Data Analysis and Reduction

Once the smoothed radar data is obtained it is appropriate to analyze the track recorded with respect to the nominal track. The first step in determining cross track error is to reduce the spherical data points to a polar coordinate

system. Since the relevant portion of each flight test is confined to an area within 10 nm of the radar site, it is probably adequate to consider a flat earth model. Thus the coordinate conversion is accomplished by:

$$r_p = r_s \cos \phi_s$$

$$\theta_p = \theta_s$$

where  $(r_s, \theta_s, \phi_s)$  are the range, azimuth and elevation of the data point in spherical coordinates and  $(r_p, \theta_p)$  are the coordinates in the polar system. It is also assumed that the waypoints indicating the desired track have also been converted. The next procedure is to assign each data point to the proper route segment by sequencing from one route segment to the next as the data point crosses the line from the center of curvature through the endpoint, in the case of an arc segment, or, for a linear segment, as the data point crosses the normal to the desired path through the endpoint. Once each point has been assigned to the proper segment, the computation of the cross track deviation is dependent on the type of segment involved. For the arc segment, the cross track deviation is the distance to the center of the curve less the nominal turn radius. For the linear segment, the deviation is measured along the normal to the desired track through the data point. Once computed, the deviations could be tabulated as a function of the along track distance rather than the relative time so that, when the results of several tests are assembled for a statistical analysis, the data points can be aggregated on a common basis. The latter procedure is facilitated by generating a second data set for each flight test in which the deviations from track are indicated at even increments of along track distance. This "normalized" tabulation is derived by interpolating between measured points.

Specifically, the data reduction should result in the following data items related to the categories previously identified.

### Flight Path Integrity

1. Cross track deviation vs time for each flight
2. Altitude deviation vs time for each flight
3. Indicated airspeed vs time for each flight
4. Groundspeed vs time for each flight
5. Magnetic heading vs time for each flight
6. Velocity vector heading vs time for each flight
7. Aggregate statistics on cross track deviation for all flights within a given test series

### Pilot Workload

1. Throttle positions vs time
2. Control yoke position vs time
3. Elevator deflection vs time
4. Bank angle command vs time
5. Acceleration command vs time
6. Pitch attitude command vs time

### Flight Crew Reactions

1. Lateral acceleration vs time
2. Longitudinal acceleration vs time
3. Maximum lateral acceleration
4. Bank angle vs time
5. Maximum bank angle
6. Flight deck angle vs time
7. Maximum deck angle

### Pilot and Controller Questionnaires

1. Compilation of questionnaire results
2. Statistical description of questionnaire results
3. Test significance of questionnaire results

To enable a reasonable basis for evaluation of the experimental test results it would be advisable to consider an analysis of the performance of aircraft executing the actual visual river approach to runway 18 at Washington National. This baseline for comparison could be obtained in the same manner indicated above from the radar data provided by the FAA's ARTS III tracking facility at DCA. The radar return signals from all transponder-equipped aircraft are recorded daily and saved for a fifteen-day period. However, the signal quality of the ARTS III data is much poorer than that derived from the EAIR tracking radar at NAFEC. Thus special pre-processing considerations are required. The method employed in a previous evaluation of approach tracks from ARTS III data (Reference 43) was a second-order curve fit about a given data point. The least-squares weighted curve fit technique was applied to valid radar points with  $\pm 16$  seconds of the desired data point. The method was shown to diminish the noise content of the radar signal by sixty-five percent, significantly improving the accuracy of the derived position data. The resulting data was of sufficiently quality to enable the flight test evaluation of RNAV equipment from position data derived from ARTS III tracking centers at the Miami and Denver terminals. The ARTS III derived track for one of the flight tests at Miami is shown as the solid line in Figure 7.2. The dashed line represents the track defined by the RNAV computer from measurements of range and bearing to the Miami VORTAC.

## 7.2 ENERGY MANAGEMENT FLIGHT TESTS

In the preceding section of this report several conventional and modified vertical control techniques have been described which logically need flight test evaluation in order to determine their utility and acceptability to pilots, passengers and ATC. As discussed in Section 6.3.2 the TCV aircraft has available flight instrumentation which could be adapted for use in evaluating these vertical

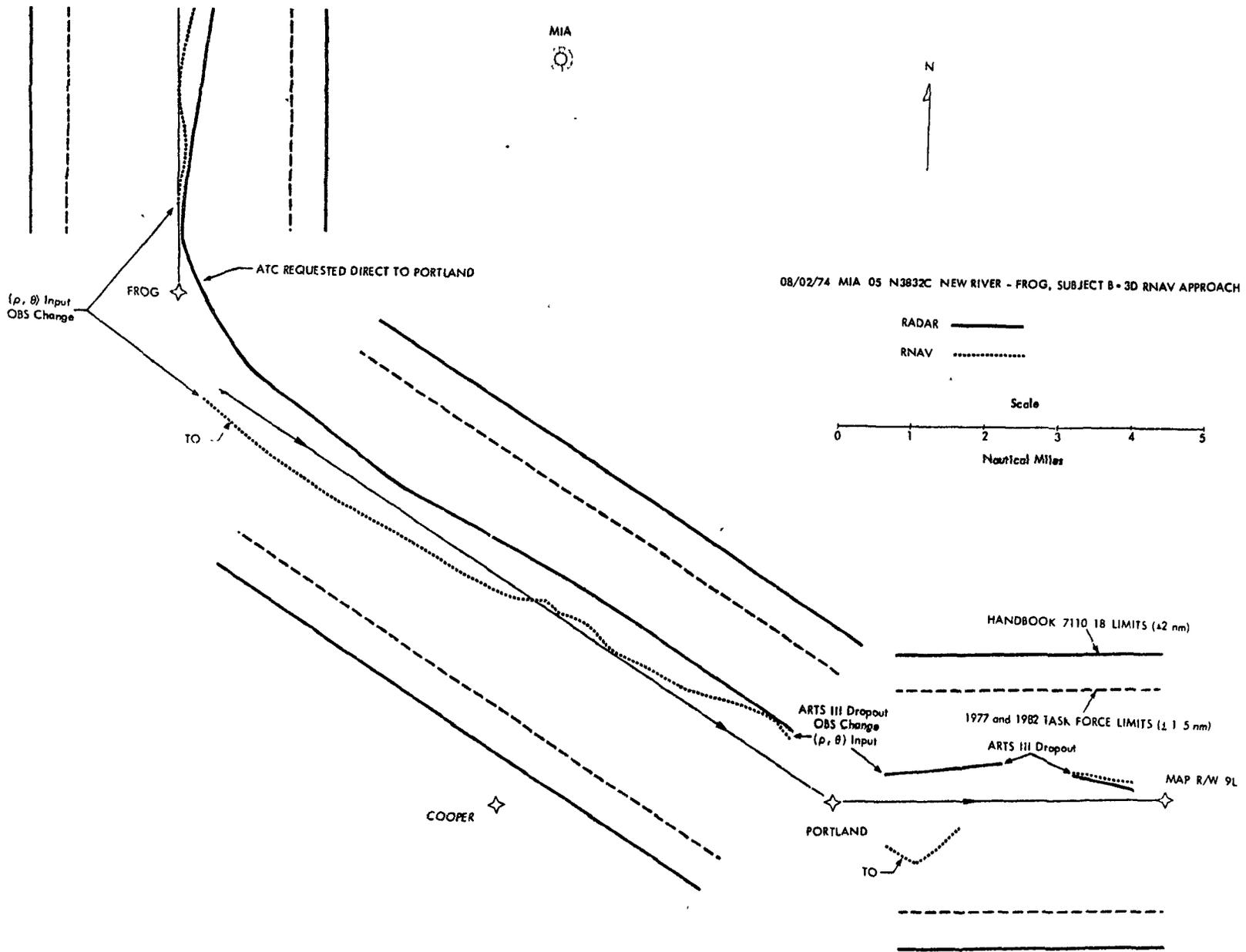


Figure 7.2 ARTS III Derived Track on Approach to Miami - Runway 9L

control techniques. In addition the TCV has parameter recording systems and navigation systems on board which will permit detailed analyses to be performed in order that the procedures can be evaluated both qualitatively and quantitatively to validate the results contained in this report. The purpose of the flights can be described in general terms by the following:

The purpose of the energy management flight test shall be to collect operational data on the use of modified climb and descent procedures in controlling the aircraft's vertical profile. These modified procedures shall include accelerating and decelerating climb and accelerating and decelerating descents. The evaluation of the results shall include the measurement of the acceptability of these procedures from the pilot's and the passenger's viewpoint. An alternate purpose of these tests shall be to provide quantitative data which will permit the flight test validation of the analytical results contained in this report. Sufficient high quality data will be recorded and processed in order that the flight test results can be directly compared to the analytical data that is generated by the simulation performance model of the B737 aircraft. This procedure will require that additional data be generated by the model to match the conditions of the flight tests, because flight test conditions are much easier to duplicate in the analytical model rather than the converse of duplicating analytical conditions in the flight test. However, flight test conditions should be controlled to the greatest extent possible under test conditions in order that quality data may be obtained.

The following paragraphs describe in greater detail the flight test plan that will permit the flight test program outlined above to be accomplished.

#### 7.2.1 Test Objectives

In very general terms the energy management flight tests have two objectives which may be stated as follows:

1. To evaluate the acceptability of energy conserving climb and descent procedures to both pilots and passengers
2. To evaluate, quantitatively, the overall energy savings that can be achieved through the use of the energy management climb and descent profiles.

The first objective has both quantitative and qualitative aspects to the problem. The quantitative features of the problem can be categorized by the following measures:

- The profile keeping ability of the flight control system while executing the energy management procedures
- The workload imposed upon the pilot during the execution of the procedures during manual flight control
- Safety aspects of the procedures as defined by speed and attack angles as a function of altitude
- Passenger comfort limits as measured by deck angles and accelerations upon the aircraft

In addition to these measures, qualitative data should be obtained from pilot questionnaires, which should be completed at the conclusion of the flight by the pilot performing the procedure. This questionnaire should address the following areas:

- Comparison to standard procedures
- Workload
- Difficulty of procedure
- Adequacy of flight instrumentation
- Acceptability of procedure from a safety standpoint

The evaluation of the procedures from an energy efficiency standpoint as stated in the second objective is somewhat harder to accomplish directly than the measures of the first objective. First, only small differences in time and fuel for the different procedures were observed from the performance model. The conditions under which these data should be carefully controlled include aircraft weights, initial and final conditions, environmental factors such as wind and temperature, and operational considerations such as ATC intervention and flight technical error. It would be impossible to obtain any meaningful data under these "real world" circumstances by directly comparing flights on a one to one basis. An alternative procedure for evaluating the energy associated parameters is to (1), perform the flight tests and measure the energy consumption parameters; and the factors which can affect the energy consumption such as those mentioned in the preceding discussion. Then, (2) duplicate these conditions to the extent possible in the simulation performance model and obtain a comparison of energy consumption between the actual flight and the modeled flight, (3), use specified flights to calibrate the model to account for aircraft to aircraft variations, (4), once the model has been calibrated perform the remaining tests and obtain comparisons between actual test data and model data, (5), check the correspondence between the data at all of the flight phases and under a variety of operating points, (6), analyze the results and estimate the validity of the model over the range of aircraft operations described in the flight plans. Finally, (7) once the model has been validated, rerun the model using the desired energy management profiles under controlled conditions to obtain energy and time data

for evaluation of the specified procedures. Consequently, the second objective may be described as that of collecting sufficient data to calibrate and validate the performance model such that the model can be used for data collection purposes.

The following paragraphs describe in some detail the test plan which can be used to accomplish the test objectives.

### 7.2.2 Flight Test Plan

The flight test plan describes the several elements that will comprise the flight test. First, there is a description of the flights that need to be flown and the conditions under which they are to be flown. Second, the data parameters that are to be recorded during the flight are identified. These parameters then must be processed to yield the performance measures that will permit the flight test objectives to be achieved. The data processing requirements are defined in terms of identifying the functional relationships between the performance measures and the recorded data parameters. Finally, data analysis requirements are identified in terms of statistical and graphical data presentation considerations.

#### 7.2.2.1 Flights

The flights that are described are selected to provide operational data concerning the acceptability to pilots and passengers of energy conservative flight profiles and to provide quantitative data to calibrate and validate an aircraft performance model which will be used to further study energy management flight procedures. The flights have been organized into a matrix of cases for ease of description and presentation. A matrix has been prepared for both climb and descent procedures. The climb cases consist of three climb procedures. They are:

- Standard constant indicated airspeed/Mach number
- Constant  $dV_I/dH$  to cruise conditions
- Constant  $dM/dH$  to cruise conditions

Four initial climb speeds at 129, 144, 159 and 175 m/s (250, 280, 310 and 340 KIAS) were considered desirable. In addition, in order to validate the B737 simulation model over a range of aircraft conditions, two initial weights were selected. These weights are representative of medium and heavily loaded aircraft weighing 38,555 and 49,895 Kg (85,000 and 110,000 lbs), respectively, at brake release. It is operationally impractical to control aircraft weight to the extent required to achieve these precise values at the initiation of climb. Consequently it is appropriate to organize speed and weight categories in an attempt to collect data on similar weight aircraft at the same airspeeds. That is, for example, on each day fuel the aircraft to the appropriate initial weight for a given series of test. For the standard climb, climb first at 129 m/s (250 kt), then at 144 m/s (280 Kt), then 159 m/s (310 Kt), etc. On the next flight day, fuel the aircraft to the same initial weight as the first test and perform the  $dV_I/dH$  tests starting at 129 m/s (250 Kt) and progressing as before. Thus, all of the runs at identical speeds will be performed at roughly the same approximate weight. In this manner some control over the initial conditions can be maintained. The final element that is used in the test matrix is the mode of the flight control system. This mode can be either manual or automatic using the AFCS. In summary, there are 3 climb procedures, 4 aircraft speeds, 2 weights and 2 flight control modes. The total number of flights is then:

$$(3 \text{ procedures}) \times (4 \text{ speeds}) \times (2 \text{ weights}) \times (2 \text{ modes}) = 48 \text{ flights}$$

For the descent portion of flight, forty-eight test flights were also planned. In descent five different procedures were considered at three different speeds. The five procedures are:

- Standard, constant indicated airspeed
- Constant  $dV_I/dH$  to 3048 m (10,000 ft)
- Constant  $d(\text{Mach})/dH$  to 3048 m (10,000 ft)
- VNAV descent at  $2^\circ$
- VNAV descent at  $4^\circ$

The three descent speeds selected are 129, 154 and 175 m/s (250, 300 and 340 Kts). For the  $dV_I/dH$ , the  $d(\text{Mach})/dH$  and the shallow VNAV descents the low speed case was deleted since little or no difference between that and the standard slow descent would be detected. Consequently, twelve speed and procedure combinations are described. To complete the tests, two nominal weights are desirable. These values are 38,555 Kg (85,000 lbs) and 45,359 Kg (100,000 lbs). In addition, data for manual and automatic flight control cases is desirable, consequently, the descent cases total 48 flights as well:

$$(12 \text{ speed/procedure combinations}) \times (2 \text{ weights}) \times (2 \text{ modes}) = 48 \text{ flights}$$

In between the climb and descent phases of flight, a short level cruise segment should be undertaken to provide some cruise data points for model validation during this period. In total the climb, cruise and descent portions should last no longer than 45 minutes and initial take off to climb area operation is estimated to take a time of not greater than 15 minutes. Consequently, average flight time per climb/descent pair should not exceed 1 hour. Therefore, the total flight test data collection phase should be accomplished in less than 48 flight hours.

#### 7.2.2.2 Data Recording Requirements

In Section 7.2.1 the basic objectives of the energy management were identified. In this section these objectives will be analyzed to determine the parameters that need to be recorded during the execution of the tests.

- Profile Attainment

In maintaining a specified profile during the airspeed vs altitude climbs and descents (standard indicated airspeed or Mach number,  $dV_I/dH$  or  $d(\text{Mach})/dH$  it is necessary to record airspeed, altitude and Mach number as a function of time. In VNAV flight, vertical track error can be obtained from airborne vertical track deviation and from ground based radar measurements.

- Pilot Workload

The measurement of pilot workload is quite subjective at best. However, the measurement of throttle, control yoke and elevator trim movements can provide some insight to differences between maneuvers as far as the complexity of the procedure.

- Safety

The safety aspects of the flight tests are also quite subjective. However, the margins that the procedure maintains between aircraft speed limits and angles of attack limits can provide information on whether marginal or unsafe flight conditions could possibly be encountered.

- Passenger Comfort Limits

The passenger comfort limits of primary importance in this test are vertical accelerations and flight deck angles.

In addition to the preceding specific types of data a questionnaire should be prepared for the pilots to make operational comments which criticize the procedures or the tests. The questionnaire should address at least the following areas:

- Evaluate the procedures and compare the difficulty of the procedure with standard techniques

- Evaluate the pilot workload
- Evaluate the flight instrumentation
- Evaluate the procedure from a safety standpoint

In addition to these data requirements it is necessary to make some measurements to validate the performance in order to achieve the second objective. The parameters that must be recorded for model validation are:

Time	Winds, crosswind and tailwind
Distance traveled	Outside air temperature
Altitude	Indicated airspeed
Fuel flow	True airspeed
Fuel consumed	Mach number
Rate of climb	

These recorded parameters will permit the flight to be reconstructed under ideal wind and temperature conditions such that calibration and validation data may be obtained for the performance model.

#### 7.2.2.3 Data Analysis and Presentation

It is anticipated that the recorded data will be processed by digital computer to produce the final test results. The processing requirements, results and data presentation requirements are discussed in the following descriptions.

##### Profile Attainment

1. Actual speed vs altitude profiles
2. Speed error vs altitude profiles
3. Statistical (mean and standard deviation estimates) description of speed error
4. Vertical track deviation vs time
5. Statistical description of speed error

### Pilot Workload

1. Throttle movements vs time
2. Control yoke movements vs time
3. Elevator deflection vs time
4. Statistical description of throttle and control surface movements
5. Frequency distribution vs magnitude of deflection

### Safety Aspects

1. Speed margins (actual speed-minimum safe speed or maximum safe speed-actual speed) vs time
2. Minimum speed margin
3. Angle of attack margins
4. Minimum angle of attack margin

### Passenger Comfort Limits

1. Vertical acceleration vs time
2. Maximum vertical acceleration
3. Frequency distribution vs magnitude of vertical acceleration
4. Flight deck angle vs time
5. Maximum deck angle
6. Frequency distribution vs magnitude of deck angle

### Pilot Questionnaire

1. Compilation of questionnaire results
2. Statistical description of questionnaire results
3. Test significance of questionnaire results

### Profile Validation

1. No wind time to climb/descend vs altitude
2. No wind fuel to climb/descend vs altitude

3. No wind distance to climb/descent vs altitude
4. No wind rate of climb/descent vs altitude
5. Temperature deviation from I.S.A. conditions vs altitude
6. Speed vs altitude
7. Fuel flow vs altitude

These results, when collected and processed into the specified presentation, will permit rapid and complete analysis of the flight test data from which follow the conclusions concerning the operational and energy conservation aspects of these flight procedures.

### 7.3 SUMMARY OF SECTION 7

A series of flight tests were proposed to determine whether curved approach procedures are a practical application of MLS. The tests involve a duplication under instrument flight conditions of the current visual River approach to runway 18 at Washington National Airport. This procedure was selected as the basis for the flight test since it represents a worst case example of a curved approach path designed for minimum noise exposure. The dual objectives of the flight test are:

- To investigate the operational implications of a curved final approach segment
- To evaluate the degree of precision attainable with MLS guidance along an arc segment approach

A series of 48 approaches were suggested to accomplish these objectives. Based on the assumption that three approaches could be executed in one hour, it was estimated that the test series would involve approximately 16 flight hours. The test sequence was designed to achieve a gradual phase-in of both the automatic flight control function and the critical landing phase. Early approaches involve only manual control functions and the execution of a missed approach procedure as the aircraft penetrates the 61 m (200 ft) level. As the series

progresses, the automatic control functions are engaged and the landing sequence is accomplished. The test series should result in:

- A statistical evaluation of cross track deviation expected along the curved approach path
- A subject evaluation of the curved approach procedure by the flight crew and the controller participating in the test series
- A identification of new equipment and revised operating procedures to facilitate the execution of the curved approach

For the energy management study, the two fold objectives of the flight test are:

- To evaluate the operational desirability of special energy management vertical control procedures
- To calibrate and validate the aircraft performance model for the B737 aircraft so that it may be used for further energy related data collection activities

In order to accomplish these objectives a series of 48 flights, which include one climb and one descent each, have been described. These flights can be described by the following parameters:

Control Techniques: Standard, constant indicated airspeeds

Constant Mach number

Constant  $dV_I/dH$

Constant  $d(\text{Mach})/dH$

VNAV descents

Speeds: 129, 144, 159 and 175 m/s (250, 280, 310 and 340 Kt) to cruise altitude

129, 154 and 175 m/s (250, 300 and 340 Kt) to descent altitude

Weights:                   Climb - 38,555 and 49,895 Kg (85,000 and 110,000 lbs)

                                  Descent - 38,555 and 45,359 (85,000 and 100,000 lbs)

Flight Control System:           Automatic or manual

The flights should take less than one hour each for a total flight time of less than 48 hours. The data processing shall produce results which will permit analyses of the following operational problems:

- Profile keeping ability of aircraft control system during execution of modified control procedures
- Pilot workload while performing the procedures
- Safety margins of the aircraft using the modified control procedures
- Passenger comfort margins during the use of modified procedures
- Pilot acceptance of modified control procedures
- Calibration and validation of aircraft performance model while executing the modified procedures

These results will be supplemented with graphics that will permit rapid comprehension of the flight test results.

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