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THE USE OF FLIGHT MANAGEMENT COMPUTERS IN AIR CARRIER OPERATIONS IN THE 1980s

I. Gershkoff

INTERIM REPORT

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16. Abstract

The use of on-board flight management computers (FMCs) in air carrier operations has the potential for significant fuel savings. This report assesses the general capabilities of the FMCs currently available. From this information, economic benefits and rates at which aircraft would be equipped were developed. Minimum-cost flight profiles were analyzed for various common conditions to determine the problems associated with incorporating the capabilities of FMCs into a heavy traffic Air Traffic Control environment.

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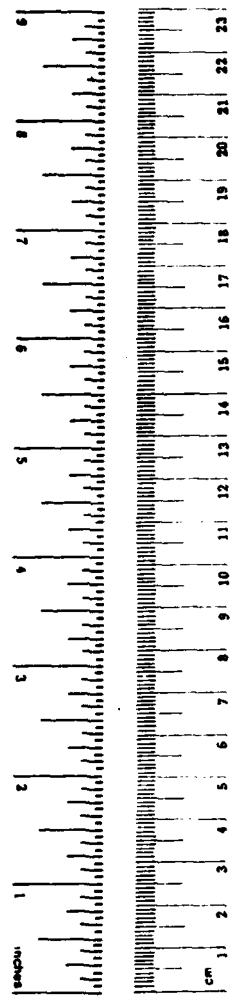
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

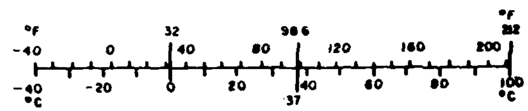
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



SUMMARY

The domestic price of jet fuel increased from about 10¢ per gallon in 1972 to about 85¢ per gallon in 1980. The percentage of airline operating cost attributable to fuel has risen from 20 to 25 percent in 1972 to about 60 percent in 1980. The airlines have responded to that fuel price spiral by initiating a number of steps to cut fuel use. Among these have been better flight planning, use of autothrottle and autopilot systems, better pilot awareness of fuel conservation procedures, use of area navigation (RNAV) when practicable, slower speed profiles, and installation of flight management computers (FMCs). The last step is one likely to have the most effect on the design and operation of the future air traffic control (ATC) system.

The use by the airlines of FMCs and other advanced avionics raises the possibility that changes to ATC procedures may be warranted to accommodate their capabilities, thus saving fuel, and possibly to exploit those capabilities for ATC purposes. The objective of this report was to develop information on predicted aircraft and avionics capabilities in the 1980s and on how these capabilities would interact with ATC procedures and equipment. The report documents three kinds of specific information: (1) current FMC systems, (2) optimal and off-optimal flight profiles, and (3) the likely percentage of aircraft to be equipped by the late 1980s. The FAA can use this information to assess how best to integrate the capabilities of FMCs into the National Airspace System and possibly to exploit these capabilities for performing routine ATC functions as well.

The first phase of this study was to characterize the general capabilities of flight management computers and other advanced avionics and their effect on air carrier flight operations. The FMCs currently under development or in production all include several basic common functions. All calculate optimal flight profiles based on aircraft lift/drag characteristics, engine performance, takeoff weight, stage length, and wind conditions. The lift/drag and engine parameters depend not only on the aircraft type but also the type of engines installed. Measurable differences in lift/drag coefficients are possible even for two identical aircraft coming directly off the assembly line. These differences must be provided for or they can lead to minor errors in FMC calculations.

The FMC manufacturers have implemented algorithms of varying complexity for calculating optimal profiles. The simplest approach is to automate the

aircraft performance tables. Another technique is to vary the values of one or two parameters until an optimal combination is found. The most complex method -- and the most computationally inconvenient -- is the control theory approach. In spite of the variety of algorithms, the different FMC models show little variation in fuel savings achieved.

Input and output in flight management computers are handled through a cockpit terminal known as a control and display unit (CDU). CDUs for advisory systems (i.e., those not coupled to autothrottle-autopilot systems) tend to be simpler than those for navigation-coupled systems because to accommodate the navigation capability the FMC must have the capability to store and display waypoint locations, distances, and relative positions in addition to proper speed and altitude. An example of each type of CDU (advisory and navigation-coupled) is shown in Figure S-1. Any FMC will also have a number of interfaces with the air-data computer, engines, and other flight instruments.

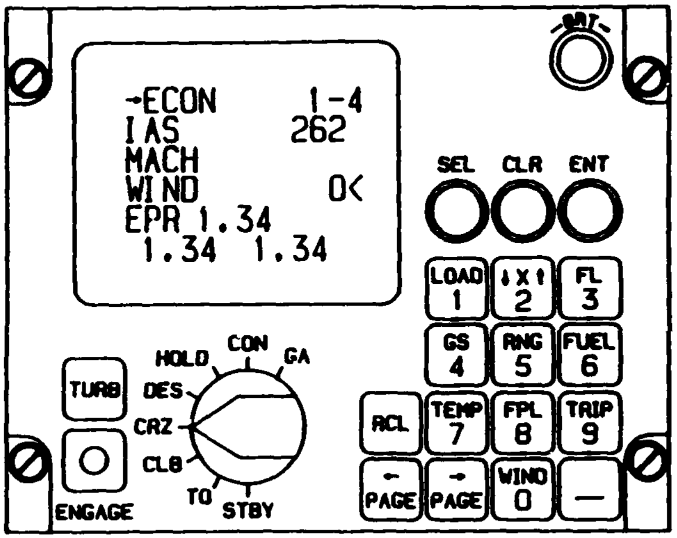
Initial costs of procuring and installing an FMC range from about \$100,000 for an austere advisory system to \$250,000 for a fully coupled system with navigation capability. Fuel savings claimed by the manufacturers range from 2 to 6 percent. Depending on aircraft size and use this represents an average payback period of three years or less. It is likely that by 1990 70 to 80 percent of the air carrier fleet will be equipped with FMCs.

Currently available FMCs have not been designed for flight route planning, handling of ATC constraints, or 4-D navigation. This is primarily a software problem; all the hardware necessary to implement these enhancements is either already installed on the aircraft or commercially available now. Future FMCs may incorporate many of the capabilities of other on-board avionics systems. For example, the 757/767 cockpit design is a clean, modular configuration with several computer subsystems, including the FMC, driving one another. By the 1990s ATC may be able to use the capabilities of FMCs to aid in its routine traffic control responsibilities by implementing a 4-D navigation system with knowledge of winds aloft and aircraft performance envelopes.

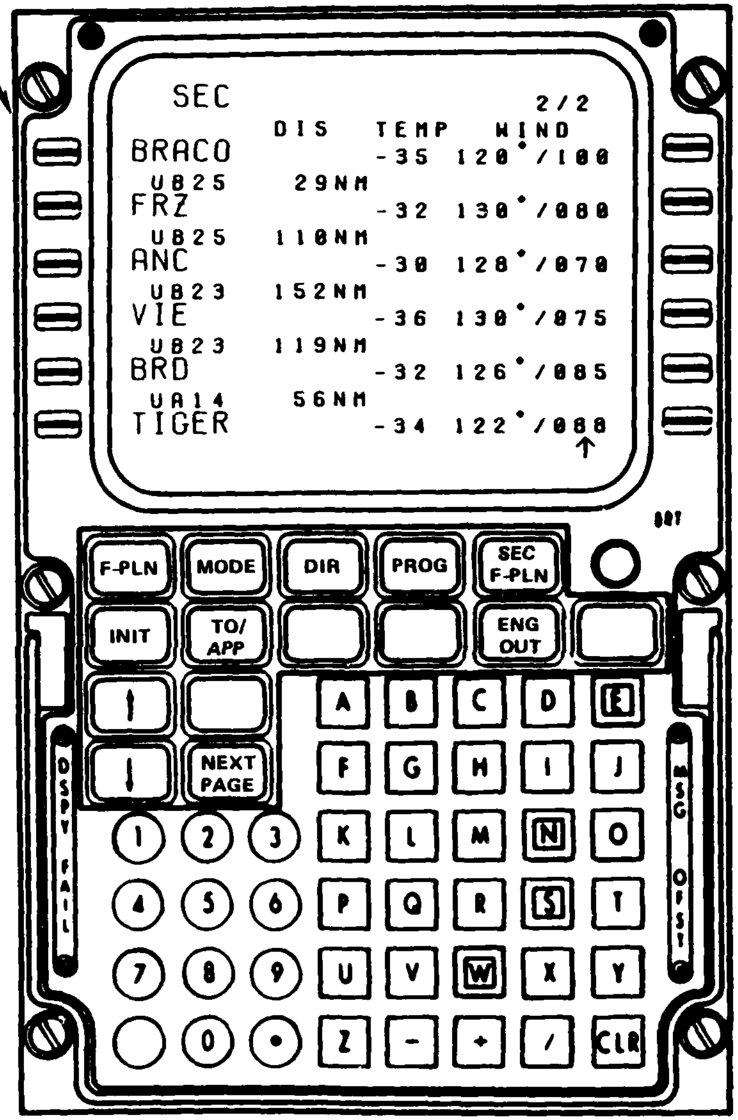
The second phase in this study was to characterize optimal flight profiles in air carrier aircraft and quantify the added costs of non-optimal flying, for whatever reason. Although fuel represents 60 percent of operating costs, a significant component of direct operating cost is time-related. To minimize cost, therefore, airlines fly profiles that are slightly faster but less fuel-efficient than minimum-fuel profiles. In a no-ATC environment the minimum-cost profile consists of a low-altitude acceleration at takeoff thrust to a target climb speed, followed by a climb at slowly decreasing indicated air speed (IAS). This is followed by a climb at constant mach, still at full throttle. The airplane is eventually leveled and the power is reduced for cruise. The plane descends at constant IAS and idle power.

The ideal, minimum-cost profile is modified by routine ATC operating constraints. Below 10,000 feet, maximum indicated airspeed is limited to 250 knots. This restriction costs fuel in climb, saves fuel in descent, Performance Navigation Computer-Flight Management System Control and Display Unit

Performance Data Computer-Performance Management System Control and Display Unit



(Courtesy of Lear Siegler, Inc.)



(Courtesy of Sperry Flight Systems)

Figure S-1. CONTROL AND DISPLAY UNITS

and loses time in both. Overall, it results in a 0.2 to 1.3 percent increase in trip costs, depending on trip duration. Aircraft must cruise at one of the ATC specified altitudes; this can cost as much as 1.0 percent more than the theoretical ideal. If flight-level separation could be reduced to 1,000 feet, these losses could be brought to within 0.2 percent of optimum trip cost. For long-haul transoceanic trips, during which altitude and speed cannot be changed, additional fuel costs of up to 3.2 percent and total costs of 1.9 percent are possible.

Minimum-cost profile descents call for idle thrust and constant indicated air speed. The sensitivity of speed to weight depends on the share of operating costs attributable to fuel. At current prices the maximum variation between an empty and a full airplane is about 15 knots; however, different aircraft types have different 15-knot speed ranges. The sensitivity of descent cost to descent speed is so low that over a 60-knot range of speeds descent cost varies less than 1 percent for all aircraft types, as shown in Table S-1. Less-than-optimum descent speeds would increase total trip costs less than 0.2 percent for short hauls, negligibly for long. Thus, a common descent speed can possibly be chosen that would be acceptable to everyone.

Table S-1. SENSITIVITY OF DESCENT COST TO DESCENT AIRSPEED (IN KNOTS -- 150 MILES UPRANGE, 30,000 FEET ALTITUDE)

Aircraft Loading		Best Speed	1 Percent Higher Cost		2 Percent Higher Cost	
			Low	High	Low	High
727	- Empty	270	240	315	230	330
	- Full	283	256	307	246	320
747	- Empty	289	264	321	254	340
	- Full	300	270	338	259	351
L-1011	- Empty	302	278	340	267	358
	- Full	306	283	338	274	352
A-300	- Empty	315	290	347	281	360
	- Full	320	294	355	284	370
DC-9	- Empty	289	262	318	250	329
	- Full	295	270	320	260	333

The speeds shown in Table S-1 assume that the descent is properly planned and executed. Costs of overshoot or undershoot were calculated at up to $5 per mile of error for an L-1011. It is about three times as expensive per mile to undershoot than overshoot because a descent begun too early must be completed with an inefficient low-altitude cruise segment.

The degree to which FMC capabilities can be exploited by ATC depends in part on how many aircraft have FMCs installed. Some aircraft are now being retrofitted with them; installation should be completed by mid decade. Most new aircraft with FMCs will have factory installations. On the basis of projected traffic mix, we estimate that from 66 to 86 percent (with an average of 79 percent) of aircraft using the top 25 major hub airports will be equipped with FMCs. Coastal gateway cities such as New York and San Francisco will have the highest rates, while regional airports like Pittsburgh and St. Louis will be at the low end. Taking maximum advantage of FMC capabilities will require a good deal of ATC ground capability, which will probably not be implemented for several years. Whatever savings the carriers can achieve before the ATC develops that ground capability will still be adequate to justify the installation of FMCs.

Cost savings offered by FMCs, principally in fuel consumption, can be up to six percent of direct operating costs, depending on aircraft type, pilot proficiency in following fuel-conservation procedures, typical stage lengths, and sophistication of the FMC. Typical savings per aircraft range from about $50,000 for 727s and similar aircraft to $150,000 for wide body aircraft. Based on a fleet-wide fuel burn of about 10 billion gallons in 1980, FMCs offer the potential to save about 200 million gallons of fuel annually.

Experience gained from using FMCs coupled with continuing improvements in electronics technology ensure a growing use of onboard computers in all phases of flight. By 1990, FMCs will be routine equipment. Additional capabilities will be added to further reduce pilot workload and complement the cost-reduction benefits offered by FMCs. Ultimately, some of these capabilities will affect ATC's way of doing business as well.

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CHAPTER ONE

INTRODUCTION

1.1 NECESSITY OF TRAFFIC FLOW MANAGEMENT

The price of all oil-based fuels increased sharply in the 1970s. Jet fuel, in particular, has increased from about 10¢ per gallon in 1972 to about 85¢ per gallon domestically in the fall of 1980. Fuel prices abroad were about 20 cents higher. As shown in Figure 1-1, the price of jet fuel roughly doubled between 1973 and 1974, doubled again from 1974 to 1978, and doubled once again from 1978 to the present. This eightfold increase in fuel price since 1973 compares to a doubling of the general price level over the same period. As a result, the percentage of airline direct operating cost attributable to fuel has risen from about 20 to 25 percent in 1972 to about 60 percent in 1980, as shown in Figure 1-2. Thus, fuel has become the dominant cost factor in operating an air carrier turbojet or turbofan aircraft, resulting in numerous changes in procedures and equipment to minimize fuel consumption or make more effective use of the fuel that is used.

At the same time, the demand for air traffic services at major hub airports continues to grow. Four airports (John F. Kennedy, La Guardia, O'Hare, and Washington National) now limit air carrier operations to a predetermined maximum at certain hours. During peak hours, arriving aircraft may be delayed, especially under Instrument Flight Rules (IFR) conditions that reduce runway capacity. Every minute spent by an aircraft circling over a crowded airport adds costs, irritates its passengers, and aggravates the nation's fuel supply problem. With carriers currently operating on thin margins, a significant delay at the destination can easily wipe out the profit from a flight. Expected growth in air traffic (both air carrier and general aviation) can only make this problem worse.

Current air traffic control (ATC) procedures are designed to handle incoming traffic in a safe and orderly manner, but not necessarily in a fuel-efficient manner. Recent studies by the Federal Aviation Administration (FAA) Office of Systems Engineering Management (OSEM) and Air Traffic Service (ATS) have demonstrated the feasibility of using algorithms to sequence traffic to maximize runway utilization and reduce delays. While these measures may reduce fuel consumption somewhat, reduction of delay was the overriding design criterion. A sequence consisting of several sharp turns and speed changes at low altitude may maximize traffic throughout, but

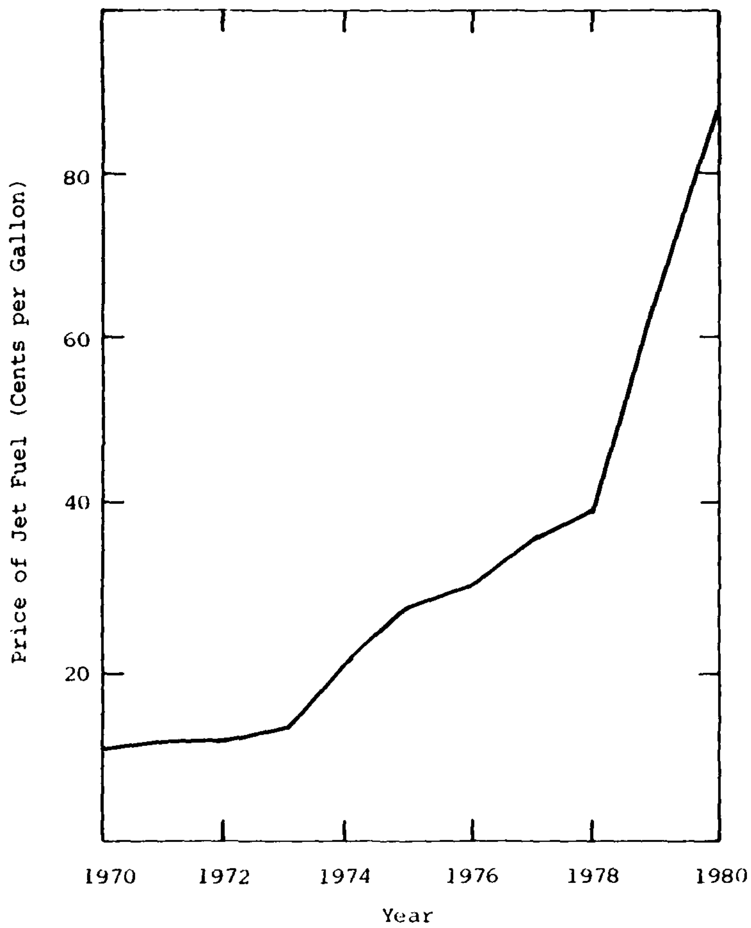

Figure 1-1. PRICE OF JET FUEL

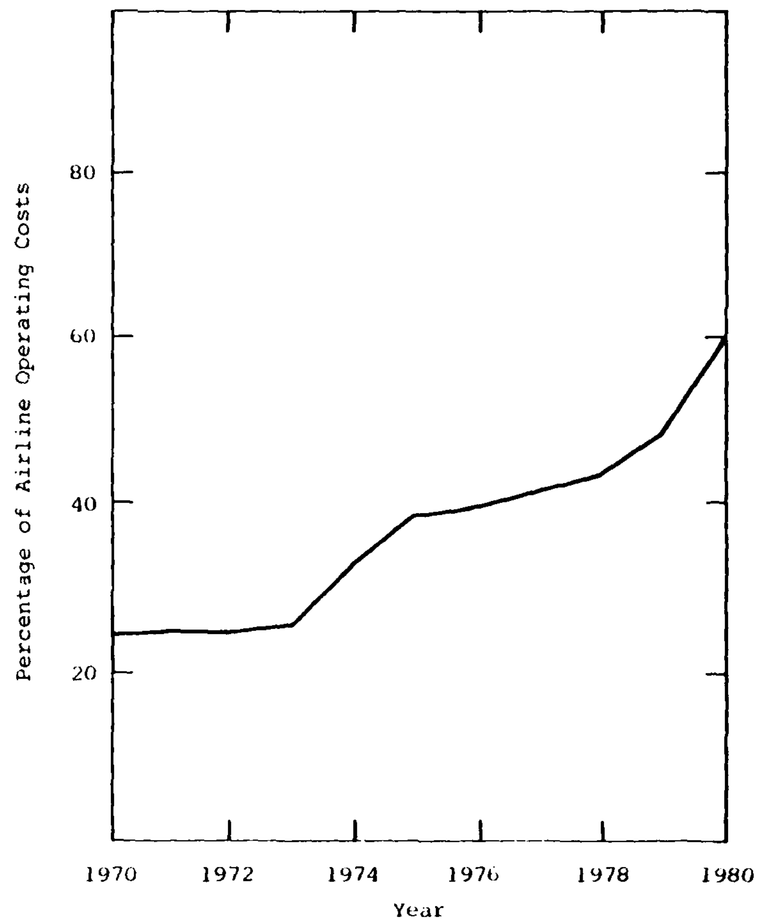

Figure 1-2. PERCENTAGE OF DIRECT OPERATING COSTS ATTRIBUTABLE TO FUEL

Source: Reference 12

it may also reduce achievable fuel savings. Metering procedures currently used at several large terminal areas transfer any delays back into enroute airspace, where they can be managed more efficiently. This has had some benefits for both traffic throughput and fuel consumption at those airports.

With their fuel bills at an all time high, air carriers are naturally paying more attention to flying their aircraft more efficiently. However, the most fuel-conservative flight profiles are not necessarily compatible with current ATC procedures. The FAA needs to be constantly investigating possible modifications to equipment and procedures to ensure that the agency remains responsive to the needs of the aviation community in addition to maintaining a safe and orderly flow of traffic.

1.2 AIR CARRIER ACTIVITIES TO CONSERVE FUEL

The airlines have responded to the fuel price spiral by initiating a number of steps to cut fuel use:

- Fleet Upgrading - The fuel price spiral has accelerated the phase-out of the fuel-inefficient jets, such as the 707 and early DC-8. Some carriers are choosing to install new engines in these aircraft rather than sell or scrap them, which is almost as good as buying a new aircraft as far as fuel consumption is concerned.
- Better Flight Planning - Most airlines use a central flight planning computer to analyze possible flight routes. These systems have an extensive data base of winds and temperature aloft information to include in these analyses. Proper planning can make optimal use of favorable winds, dodge weather systems, and save both trip time and trip fuel.
- Use of Autothrottle-Autopilot Systems - This equipment is capable of controlling thrust and pitch to maintain a given speed or altitude with much more precision than a pilot could. Although these systems were not installed specifically to save fuel, they minimize the fuel-inefficient throttle changes required to keep the aircraft on the prescribed profile. Typical fuel savings range from 1 percent for wide-body aircraft to about 2 percent for smaller jets and business and commuter aircraft.
- Better Pilot Awareness of Fuel-Conservation Procedures - Many airlines rate pilots' performance partly on aircraft fuel consumption during their flights. Pilots therefore have ample incentive to become aware of fuel conservation procedures and to follow them. Airlines are helping pilots by developing long-range cruise (LRC) schedules as guidelines for fuel-efficient operation of the aircraft.
- Installation of Area Navigation Systems - Area navigation (RNAV) systems permit the pilot to go directly between any two points without having to pass over intermediate VHF omnidirectional ranges (VORs) or using the standard jet airways. The net effect of RNAV is to reduce trip distance. Savings in distance traversed

vary according to stage length and how well the origin and destination fit into the published airways structure. A typical saving is about 2 percent. RNAV also offers additional flexibility in flight planning since trip way points can be established anywhere. RNAV flight plans are not always accepted by ATC, particularly in the high density Northeast corridor.

- Slower Descents - Until recently, most airlines typically flew high-speed, idle-thrust descents at 340 knots indicated air speed (KIAS) or faster, often using speed brakes at low altitude to reduce speed as necessary for a landing approach. The fuel-optimal descent speed is in the 220 to 280 KIAS range, depending on aircraft type and weight. In recent months, more and more airlines have encouraged their pilots to make slower descents to save fuel. The pilots are not always able to follow those procedures, however, because ATC often requests a higher descent speed or forces the aircraft to hold at an intermediate altitude. Nevertheless, some benefits have been realized.
- Installation of Flight Management Computers - On-board flight management computers (FMCs) calculate a cost-optimal climb, cruise, and descent flight profile based on the performance characteristics of the airplane. Many of these performance computers are coupled to autopilot and autothrottle systems that assure that the computed trajectories are followed precisely. Flight management computers are also often coupled to the aircraft navigation system. When they are, they can calculate the best profile and execute it within the framework of the flight plan.

1.3 ATC INTERACTIONS WITH AIR CARRIER ACTIVITIES

Most of the above steps have little or no effect on ATC. For the most part, controllers and their associated equipment do not care whether or not an aircraft has an autothrottle or how a particular route of flight was chosen. However, in heavy traffic, the use of RNAV, slow descents, or flight management computers may burden the controller. In any ATC environment where there is more than one airplane in the sky, competition for airspace will inevitably develop and must be resolved. Thus, the controller may often be forced to vector an aircraft off course or mandate a non-optimal descent speed (from the pilot's point of view) in order to achieve the controller's primary goal of maintaining separation.

The installation of FMCs and other new avionics raises the possibility that changes to the ATC procedures may be warranted to accommodate these capabilities and possibly exploit them for ATC purposes. This would help achieve the goal of reducing systemwide fuel consumption and delays, while making the best possible use of existing runway capacity.

1.4 OBJECTIVE AND SCOPE OF THE STUDY

This study characterized the fuel-saving aircraft and avionics capabilities anticipated in the 1980s. Its overall objective is to develop information on aircraft and avionics capabilities in the 1980s and how these capabilities would interact with air traffic control procedures and equipment. The FAA can then use that information to assess how best to integrate the capabilities with existing ATC resources. Since some aircraft and avionics capabilities are limited by constraints in existing ATC procedures, an assessment of possible trade-offs between delay, fuel efficiency, and capacity will be presented. On the basis of the results of this study, the FAA could conduct benefit analyses to assess whether proposed changes in procedures would improve the efficiency of the National Airspace System. This study will develop the theoretical level of achievable savings. Specific programs to achieve these savings will not be explicitly considered.

The project has consisted of two tasks. The first was to characterize the capabilities of various types of advanced avionics that are expected to become available in the 1980s. The emphasis was on flight management computers because they directly affect the aircraft flight paths and, therefore, affect ATC. Also included are other types of advanced displays, such as electronic horizontal situation indicators (EHSIs) and advanced sensors and data links that would be capable of direct communication with the ground.

The second task was to characterize aircraft fuel consumption under various conditions. Fuel-optimal flight profiles were calculated as a function of aircraft type, loaded weight, stage length, and wind conditions. Preferred airline operating characteristics were factored into this analysis as well. From the optimal profiles, the penalty for flying off the optimal routes, for whatever reason, can be calculated. Using the estimate of flight management computer equipment identified in Task 1, the probable effect on terminal sequencing at major hub airports can be assessed.

1.5 ORGANIZATION OF THIS REPORT

Chapters Two and Three discuss the general capabilities and engineering design of flight management computers. Chapter Two describes capabilities and features seen primarily from the pilot's standpoint and used in the course of a flight. Chapter Three concentrates on the engineering design -- the hardware, required interfaces, input-output mechanisms, and flight deck configuration. Chapters Two and Three deal with Task 1.

Chapters Four and Five discuss typical flight profiles that would be desired by pilots in normal operations. Chapter Four covers the issues in the climb and cruise phases of flight. Climb and cruise profiles are examined for a mix of aircraft types and gross weights. Sensitivities to temperature, wind, and routine ATC restrictions are assessed. Chapter Five covers these same issues for descent into the terminal environment. Chapter Five also discusses the cost consequences of non-optimal descents, either in descent airspeed or in point-of-descent calculation. Optimal management of mandatory ATC delays is another issue of interest in this chapter.

Chapter Six examines the issues affecting the use of flight management computers in the 1980s and 1990s. It looks at the potential for the use of FMCs to assist in air traffic control functions. It develops a forecast of the percentage of FMC-equipped operations in the late 1980s. This chapter also identifies the ATC issues that must be resolved between pilot and controller. Chapters Four to Six cover Task 2 of the study.

Chapter Seven presents the overall conclusions of the study and identifies sensitive areas for which further work could be performed.

A bibliography of documents reviewed in the course of the study is also provided. Appendix A presents a table of the general capabilities of flight management computers currently under development or in production, and Appendix B documents the fuel-burn model on which much of the analysis in Chapters Four and Five was based.

CHAPTER TWO

GENERAL CHARACTERISTICS OF ON-BOARD FLIGHT MANAGEMENT COMPUTERS

2.1 INTRODUCTION

The design and development of on-board flight computers for managing flight profiles is quite recent, dating only from the mid 1970s. Before 1974, fuel costs amounted to about 25 percent of direct operating costs. Airlines were concerned with the fuel bill, but had more concern over fleet utilization and other time-related costs of operation. Furthermore, there was competitive pressure to conduct fast flights, and jet fuel was always available at reasonable prices. Thus, there was little incentive for the air carriers to conserve fuel.

The oil price shocks that have sent the price of jet fuel from 10 cents to 85 cents per gallon have changed those attitudes. Fuel costs are now the dominant cost factor, and fuel is not always available. Profit margins are thinner as well. Consequently, priorities have changed. Competitive pressures are still important, but airline managers are spending much more time striving to improve the fuel efficiency of their fleets. It was primarily this factor that spurred the development of flight management computers.

Coincident with the increase in fuel prices have been rapid advances in computer technology. Hardware has decreased in price by about an order of magnitude during the 1970s. At the same time, the benefits achievable through use of on-board computers have increased. Therefore, the payback period for flight management computers has steadily decreased to the point that the FMCs can be a very profitable investment.

Flight management computers reduce operating costs, principally by reducing the consumption of fuel. The savings are achieved through a variety of capabilities and features. Many of these are common to all models currently available or being designed. This chapter discusses those common characteristics of flight management computers and explains how they help the pilot conduct a more efficient flight and reduce his workload. On the basis of calculations of expected costs and fuel benefits, the rates of equippage and the spectrum of flight management capabilities expected in the 1990 air carrier fleet were also estimated.

2.2 DEFINITIONS

Because of the often confusing terminology used by the airframe and avionics manufacturers, it is worthwhile to define the most common flight management computer system configurations.

Performance Data Computer (PDC) - This computer calculates open-loop optimal power setting, cruise altitude, and airspeed at each moment of the flight. It is strictly an advisory system; it is not coupled to autothrottle or autopilot systems. Through interfaces with other avionics, the system knows the aircraft's altitude and approximate downrange distance (2-D capability); however, it does not have a navigation capability enabling it to pinpoint the aircraft's specific position in the airspace. Thus, the top-of-descent point must be calculated in terms of distance-to-go, and the pilot has to decide when this point is reached. PDC may also refer to the performance computer alone, without including any supporting interfaces.

Performance Navigation Computer (PNC) - This is a PDC with navigation capability. The actual navigation system used is not important; PNCs have been developed using VOR/DME, DME/Doppler, Omega, or INS systems. A PNC could be developed with an open-loop 3-D or 4-D capability. That is, it could set a target power setting, airspeed, and pitch that, if followed, would result in the aircraft arriving at a given position and altitude (that is 3-D capability; use of 4-D would result in arriving at the designated point at a specified time). However, such a system would not have any control of the aircraft throttles or flight controls that would be used to correct flight profile errors and thereby ensure that the aircraft was remaining on track.

Performance Management System (PMS) - A PMS is a PDC coupled to the aircraft autothrottle and/or autopilot systems. It can calculate the optimal climb, cruise, and descent profiles and then fly those profiles. The pilot still has to perform all navigation functions. Coupling minimizes deviations from the optimal profiles and therefore minimizes costly and abrupt changes in thrust and pitch. However, the coupled PDCs do require the pilot to initiate any changes in the flight profile to ensure that he retains ultimate control of the aircraft.

Flight Management System (FMS) - An FMS is a deluxe system that incorporates the flight profile algorithms of a performance data computer, has an interface with the navigation system, and is coupled to the autothrottle and autopilot. Theoretically, the system should be able to fly the airplane from shortly after takeoff to final approach. The potential exists for a full 4-D capability since the system has both the navigation data base and the closed-loop control of the aircraft; however, the software used in some current FMSs was not designed to have 4-D capability although it could be modified easily to do so.

Flight Management Computer (FMC) - FMC is a generic term used to signify any or all of the above four types of systems.

2.3 FACTORS AFFECTING FLIGHT PROFILE MANAGEMENT

The flight management computers currently under development or in production all have several basic functions in common. All calculate optimal flight profiles based on aircraft lift and drag characteristics, engine parameters, take-off weight, stage length, and wind conditions. The systems calculate the optimum climb speed; for some units the climb speed will vary with altitude. Each system will compute an optimum cruise altitude and adjust it to the nearest allowable flight level (see Figure 2-1). As fuel is burned off, the optimal cruise altitude increases, and most systems will indicate the need to step climb when flight at a higher flight level becomes more fuel efficient. PDCs and PMSs can calculate a top-of-descent point in terms of distance-to-go; PNCs and FMSs can compute the exact possition to begin descent. Optimal descent is usually at a power-off, constant indicated airspeed (IAS).

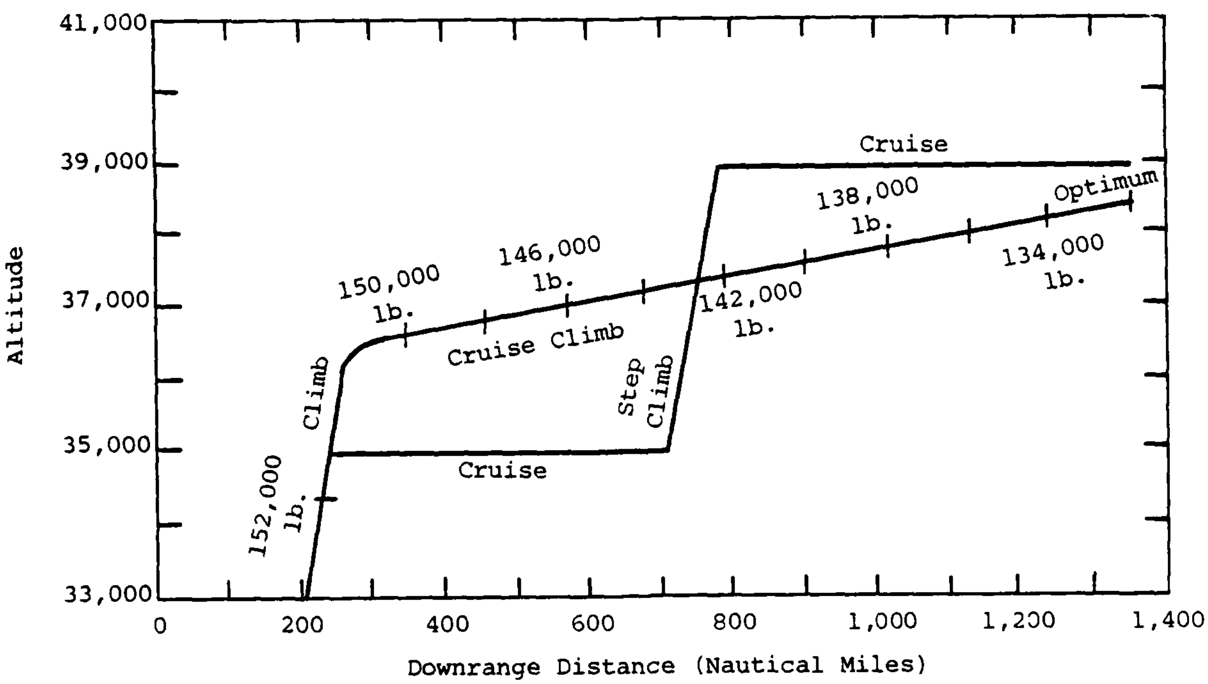

Figure 2-1. STEP CLIMB/CRUISE CLIMB PROFILE (B727-200)

Software must be tailored to the lift and drag coefficients of the airplane in which the flight management computer is installed. This depends not only on the aircraft type but also the type of engines installed. As airframe and engines age, wear causes subtle changes in drag characteristics that can result in the true values of these coefficients drifting away from the values stored in the FMC. Although this is not a serious problem, it can lower aircraft performance by a few tenths of a percent. Even two identical aircraft coming directly off the assembly line may have measurable differences in lift and drag coefficients. Age, maintenance, and manufacturing variations can cause a substantial difference in thrust output from apparently identical engines. Avionics manufacturers and purchasing airlines are understandably reluctant to customize software to a particular airplane -- it is costly enough (estimated at $250,000 by one manufacturer) to calibrate the software for all reasonable combinations of aircraft and engine types. The savings resulting from a customized calibration - or recalibration every few years - would not justify the considerable expense. Therefore, manufacturers will calibrate lift and drag coefficients only once for a particular airplane and engine combination and hope that they will be accurate enough for other aircraft of the same type. Any inefficiencies due to errors in these coefficients must be considered unavoidable since the cost of correcting these errors would exceed the benefits from doing so.

Aircraft gross weight is another important factor affecting the optimal flight profile. Other things being equal, heavier aircraft fly most efficiently at airspeeds faster than the most efficient airspeeds for lighter aircraft, but they cruise at a lower altitude and take more time to reach that altitude. They also require more power during cruise. However, power setting during optimal climb and descent is not affected by weight, since in climb the aircraft is operating at maximum climb power, and in descent the aircraft is idling, regardless of weight. Any flight profile analysis also must consider that gross weight decreases as fuel is burned. For a transcontinental or transatlantic flight, the fuel burned during the flight can amount to about one quarter of takeoff weight. Fuel efficiency is also affected by the distribution of weight in the aircraft and the position of the center of gravity. However, under ordinary circumstances this is a minor factor since the proper center of gravity is carefully computed in the flight planning process and no currently available flight management computer takes it into consideration.

Another important factor affecting flight profile management is weather, particularly temperature and wind. Temperature affects aircraft performance: on colder days, the air is denser; therefore, the aircraft can climb faster and higher and operate slightly more efficiently. Wind affects the optimal speed of operation as well. When confronted with a headwind, the pilot should increase airspeed over the most fuel efficient no-wind speed, thereby spending less time in the air and reducing the negative effects of the wind. Similarly, when flying with a tailwind, the pilot should decrease airspeed, thereby staying in the air longer and letting the wind do more of the work.*

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*This is true for the typical aircraft operating in a steady-state cruise configuration at or very near its maximum lift/drag ratio.

These effects will be quantified in Chapters Four and Five. Also, the presence of significant weather systems or turbulence might affect the choice of routing or cruise altitude. A flight path that is not optimal for fuel conservation might in fact be the best choice if it increases timeliness, passenger comfort, or safety. For example, a pilot could have the option of climbing to the next higher flight level and improving fuel conservation and performance, but he might choose not to do so because that level would allow him too small a margin of safety between the stall and mach buffet margins. (Buffet problems are further discussed in Section 4.5.1.)

All of the factors listed above are subordinate to the airlines' prime goal of maintaining profitability by operating safe, smooth, timely flights full of satisfied customers. Fuel efficiency will often be sacrificed if by doing so, passengers on a late flight will be able to make their connecting flights, or an area of turbulence can be avoided. Airlines believe that if they do not make such efforts for their passengers' comfort and convenience, they will lose passengers to airlines that do. However, when these overriding considerations are not present (most of the time), there is every reason to minimize costs any way possible.

2.4 BASIC PERFORMANCE MODELING APPROACHES

The flight management computer manufacturers use algorithms of varying complexity in calculating optimal profiles. This section describes the most commonly used algorithms and the advantages and disadvantages of each.

The simplest approach is to automate the aircraft performance tables. These tables characterize flight performance on the basis of known parameters such as airspeed, gross weight, and temperature. At each stage of the flight the FMC can search through the table and find the best set of parameters for the conditions existing at that moment in the flight. If the flight conditions do not fit perfectly into the stored tables, the FMC will interpolate them. A sample performance table is shown in Table 2-1. It was produced by use of the VARYMOD program developed by the FAA Office of Environment and Energy; it is documented in References 13 and 55. It gives cruise performance at 25,000 feet in terms of nautical miles per 1,000 pounds of fuel as a function of gross weight and mach number. This altitude might be suitable for stage lengths of about 300 miles; similar tables would exist for higher altitudes applicable to longer stage lengths. At any particular weight, the computer can easily find the best mach number to fly by searching through the table. This approach works fairly well in steady-state cruise, when altitude and weight change slowly. It does not work as well during climb and descent, when conditions are changing more rapidly. The tables may also require a lot of storage, although this requirement can be cut somewhat by fitting the data in the table to a regression equation. For example, the data in Table 2-1 could be expressed as an equation of the form

$$\text{NM}/1{,}000 \text{ lbs} = C_0 + C_1W + C_2M + C_3M^2$$

Table 2-1. SAMPLE PERFORMANCE TABLE FOR 727-200

NMI./THOUSAND POUNDS
AS A FUNCTION OF W (COLUMNS) AND VA (ROWS)

VA/W	110000.00	120000.00	130000.00	140000.00	150000.00
.4000	43.18	38.53	34.50	30.99	27.94
.4200	46.14	41.50	37.42	33.82	30.65
.4400	48.73	44.18	40.10	36.47	33.24
.4600	50.92	46.52	42.52	38.91	35.66
.4800	52.71	48.51	44.64	41.11	37.88
.5000	54.11	50.15	46.46	43.03	39.88
.5200	55.14	51.45	47.96	44.68	41.63
.5400	55.84	52.43	49.16	46.06	43.13
.5600	56.24	53.11	50.07	47.16	44.39
.5800	56.39	53.52	50.72	48.01	45.40
.6000	56.30	53.70	51.13	48.62	46.18
.6200	56.03	53.67	51.33	49.01	46.75
.6400	55.60	53.47	51.34	49.22	47.13
.6600	55.03	53.12	51.19	49.25	47.33
.6800	54.37	52.65	50.90	49.13	47.37
.7000	53.62	52.07	50.49	48.89	47.28
.7200	52.80	51.42	49.99	48.54	47.07
.7400	51.94	50.70	49.42	48.10	46.76
.7600	51.05	49.93	48.78	47.59	46.37
.7800	50.13	49.13	48.09	47.01	45.91
.8000	49.20	48.30	47.36	46.39	45.39

THIS TABLE REFLECTS THE FOLLOWING:

AIRPLANE: B727 UNIT = NMI./THOUSAND POUNDS
V1 = VA V2 = VA VA = ROW
ALL SPEEDS ARE MACH NUMBERS
H1 = 25000. H2 = 25000. HA = 25000.
D = VARIES T = 60.00 W = COLUMN
DRAG CONDITION: CLEAN

where

NM/1,000 lbs	=	Nautical miles per 1,000 pounds of fuel
W	=	Aircraft gross weight in pounds
M	=	Mach number
C_0, C_1, C_2, C_3	=	Coefficients to be estimated

With the proper values of $C_0 \ldots C_3$, the above equation will produce Table 2-1 to a high degree of accuracy. Using this technique, storage requirements are cut from 60 entries to 4, and there is no need to interpolate. However, the equation must be evaluated each time an element from the table is desired, so the technique will cost processing time.

A more complex approach is to conduct a one- or two-parameter iterative optimization. In this approach the software sets values for key parameters, then calculates operating performance for flying under the set conditions between the current location and a second point further downrange. The process is repeated again and again for a different set of parameters until the computer has satisfied itself that the best combination has been found. This method is applicable to all phases of flight but might require a large amount of processing time to produce an optimal result. Generally some assumptions about the nature of the solution are needed to hold computing time to a tolerable level. Optimizations involving more than two variables are not practical for this reason.

The most complex method is the control theory approach. Several state equation models have been developed to explain aircraft dynamics, but only the simplest of these - a single variable energy state formulation - has been solved. This approach probably produces the most detailed profiles but requires storage for intermediate calculations and substantial computer time as well. Both of these limitations are significant in a small on-board computer because storage is limited and the central processing unit (CPU) has several other jobs to do besides calculating the profile. Control approaches can be developed to optimize the profile as a whole rather than to break down the trip into climb, cruise, and descent and optimize each section individually, as must be done in a parametric approach.

Another drawback of the control method is that although the profiles generated by this technique are marginally more efficient than those produced by other methods, they can be difficult for the pilots to follow. For example, if the profile calls for speed changes during climb, the pilot must continually monitor and adjust airspeed to keep on the proper track. The frequency and magnitude of throttle and pitch movements is much higher when the target airspeed is changing than when it is fixed. Control movements cut into fuel efficiency. There is some question whether the benefits of the better profile outweigh the loss of efficiency due to the excess control movements. However, the control theory profiles are certainly better when the aircraft control movements can be minimized through the use of an autothrottle system.

The FMC manufacturers use combinations of the above algorithms, exploiting the strengths of each. The composite algorithms used in the FMCs are trade-offs between mathematical complexity and computational feasibility. Any algorithm is only a model of aircraft performance, and, as such, it cannot possibly account for every factor affecting flight. All algorithms must handle sensitivities believed to be important and hope that that will be sufficient. In spite of a wide variety of flight profile algorithms used by the various manufacturers, there does not appear to be an overwhelming difference in overall fuel performance among the different FMC models. Fuel savings claimed range from 2 percent to 6 percent of trip fuel, depending on stage length and pilot proficiency in achieving fuel-efficient flight without an FMC.

2.5 USER INPUTS AND OUTPUTS

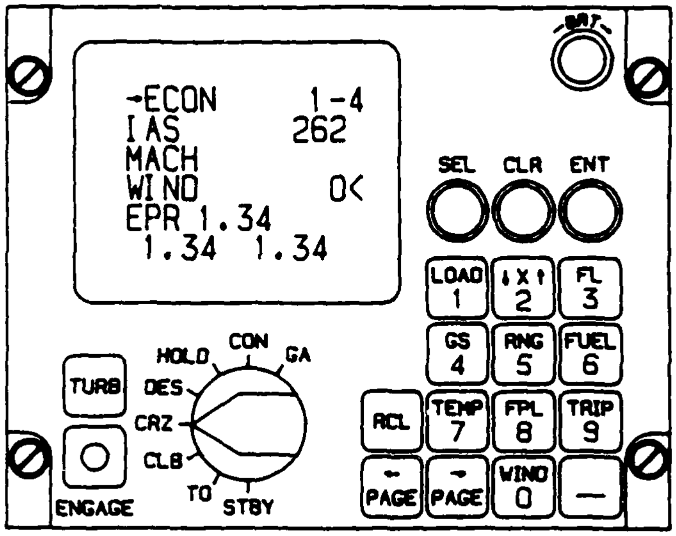
The user interfaces on flight management computers are simply and efficiently designed to enable pilots to learn to use them in just a few hours of training.

The control input-output device is a cockpit display terminal coupled to a simple keyboard. This is known as the control and display unit (CDU). It is usually located between the captain and the first officer so that both have access to it. Some systems have an option for dual CDUs so that either can query the PDC independently. The display medium varies by manufacturer. Some use a cathode ray tube (CRT); one uses a plasma discharge display that produces a bright orange color display; others use light emitting diodes (LEDs) or segment displays. All are well accepted by the pilots who use them; there do not appear to be major human factors problems with any of the systems examined.

All systems also display target EPR (power setting) and airspeed figures for the pilots to follow. For PMSs and FMSs, the outputs set bugs for the autopilot and autothrottle systems. For PDC systems, the computer will highlight target airspeed and thrust settings directly on the instruments or display this information in a second display unit located in a prominent place in the cockpit, where the pilot can include it as part of his routine instrument scan. Most pilots say they prefer target settings on the instruments.

The CDU for the Lear Siegler PDC is shown in Figure 2-2. Its dimensions are 4 1/2 inches by 5 3/4 inches. CDUs for PNCs and FMSs tend to be larger (5 3/4 inches by 9 inches) because of the increased requirement for navigational waypoint data. These sizes are compatible with avionic displays already in the cockpit.

For PDCs and PMSs most manufacturers organize data according to a "mode" and "page" structure. Mode indicates the phase of flight of interest;



(Courtesy of Lear Siegler, Inc.)

Figure 2-2. PERFORMANCE DATA COMPUTER-PERFORMANCE MANAGEMENT SYSTEM CONTROL AND DISPLAY UNIT

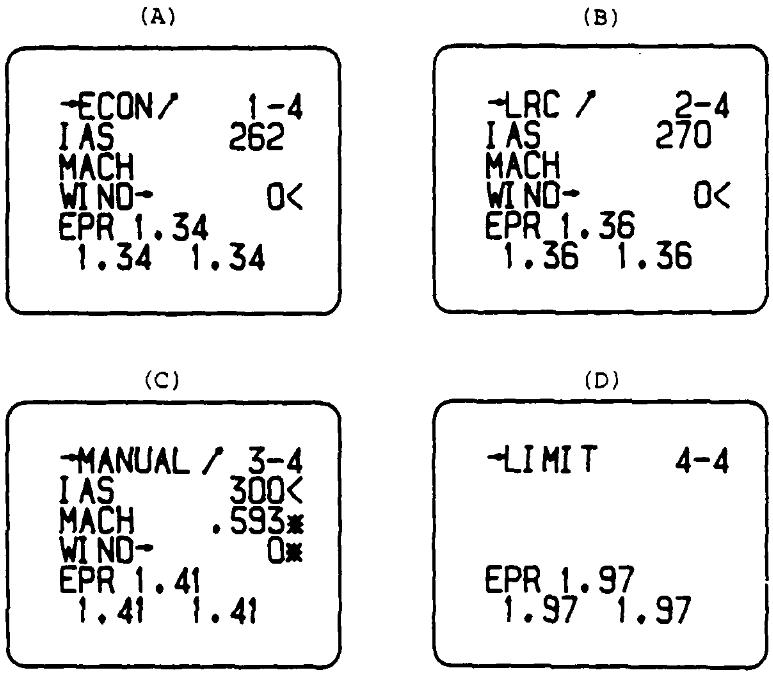
page is a subclassification representing specific performance goals or options. For example, the Lear Siegler PDC contains 9 modes:

- STBY - stand by (equipment self-test)
- TO - takeoff
- CLB - climb
- CRZ - cruise
- DES - descent
- HOLD - hold
- CON - continuous EPR limit (used for engine-out and other unusual situations)
- GA - go around EPR limit
- TURB - turbulent air

Within each mode, there is one or more pages that can be selected by the pilot. For example, the pages available for the CRZ are the following:

- ECON - minimum-cost speed
- LRC - long-range cruise speed, taken from operating handbook
- MANUAL - crew selects the speed
- LIMIT - maximum cruise EPR

Sample displays for these pages are shown in Figure 2-3.



(A) **ECON.** Gives you the most economical cruise speed.

(B) **LRC.** Long Range Cruise speed.

(C) **MANUAL.** Allows you to select your own cruise speed.

(D) **LIMIT.** Displays maximum cruise EPR.

(Courtesy of Lear Siegler, Inc.)

Figure 2-3. CRUISE MODE PAGES

The displays are fairly self-explanatory. A separate EPR number is given for each engine; normally, all will be identical.

For commonly used procedures, the FMC will cycle through the relevant pages and prompt for whatever data are needed. At a minimum the systems require the pilot to enter takeoff elevation, gross weight, fuel weight, and the time/fuel cost trade-off factor. This can be done before takeoff as part of the preflight checklist. Most other data can be obtained automatically from engine instruments. If the pilot has further information about temperature or winds downrange, it can be manually entered.

In the course of flight the system can be queried at any time for flight progress information. Figure 2-4 shows pages available for the RNG (range) function, which would normally be used in the CRZ (cruise) mode. The pages correspond to whatever cruise option was selected. In addition there is an engine-out page to handle situations where an engine is lost in flight. Some other performance functions are LOAD (initial data load), FUEL (fuel remaining and fuel to destination) FPL (flight planning), and WIND (measured winds aloft).

PNCs and FMSs use a more complex but more flexible data-entry system. The CDU from the Sperry A-310 FMS is shown in Figure 2-5. The pilot selects a line to be modified by pressing one of the buttons on the side of the display. He can then modify or replace that line; this is his scratch pad. When he is ready, he can enter the data into the system by pressing a different button.

PNCs and FMSs can display waypoint locations, distance to waypoints, and other useful data. These displays are pages like performance data pages and may be modified if the need arises, but even the most capable FMS cannot tell the pilot the new optimal flight path if there has been a deviation from course (due to weather, for example). That is, as soon as the problem which caused the deviation has been cleared, the pilot must decide whether to proceed directly back to the original flight path, intercept it further downrange, or proceed to destination by an entirely different route; and the FMS cannot help him make this decision. Once a decision has been reached, the pilot can key in the new flight path or modifications in the old one and re-engage the FMS.

The page displayed in Figure 2-5 shows winds and temperature aloft over the proposed route of flight. The display can be quickly changed to show time en route, flight level, mach number, trip fuel, or a number of other things. The flight plan is revised by adding or deleting waypoints in the flight path.

By providing accurate, timely data to the crew, FMCs offer significant non-economic benefits to airlines. Crew members seldom need to consult airline flight manuals for routine performance information, since the FMC will have this readily available. With many frequent calculations based on readings from engine instruments automated, crew members are freed for other duties. Reducing crew workload permits the crew to spend a higher percentage of time monitoring instruments and scanning for traffic and therefore conduct a safer flight. Coupling the FMC to autopilot and autothrottle systems relieves the pilots of the tedious and time-consuming job of keeping the aircraft on its prescribed track and reduces workload further.

While FMCs are currently being installed primarily for the fuel savings they offer, additional benefits may develop as the systems evolve. Data links can be used for transmission of flight data to and from company dispatchers. This could make the aircraft more responsive to changes in wind conditions on a long-haul flight. Ultimately, the capabilities of FMCs

```
RNG ECON   1-5
 901-A+H 3:00
1376-E   4:39
AT FL    150<
WIND-      0*
```

Economy

```
RNG LRC    2-5
 898-A+H 2:50
1375-E   4:28
AT FL    150<
WIND-      0*
```

Long Range Cruise

```
RNG MANUAL3-5
 865-A+H 2:19
1306-E   3:35
AT FL    150<
WIND-      0*
M.593*IAS300*
```

Manual

```
RNG E/OUT 4-5
 671-A+H 1:22
1008-E   2:04
AT FL    150<
WIND-      0*
M.786*IAS402*
```

Engine Out

```
RNG HOLD   5-5
TIME-A+H 3:09
    -E   4:54
AT FL    150<
```

Holding

XXXX A+H XXX: Distance and time until all fuel is used except Alternate + Holding.

XXXX E X:XX: Distance and time to empty tanks.

AT FL: The display initially shows the present FL. Any desired FL may be entered.

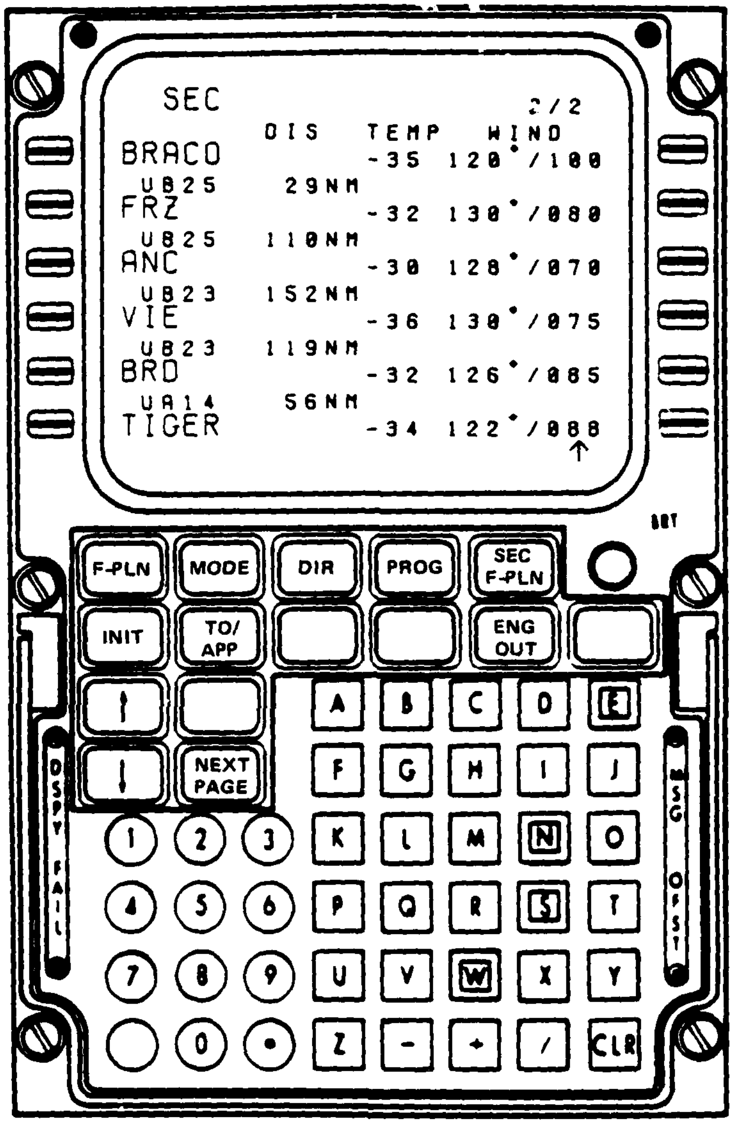
WIND: The display initially shows the wind component used in the flight modes. Any desired wind component may be entered.

M.XXX IAS XXX: The display initially shows present Mach number and IAS or, if a speed has been entered in CRZ MAN, this speed is used for RNG calculation.

For the HOLD page, holding endurance can be determined at any altitude by entering the desired FL. If the flight level is changed, time is computed for an ECON climb or descent plus the holding pattern time. Note that in a hold situation, distance and wind are not considered.

(Courtesy of Lear Siegler, Inc.)

Figure 2-4. RANGE (RNG) PERFORMANCE FUNCTION



(Courtesy of Sperry Flight Systems)

Figure 2-5. PERFORMANCE NAVIGATION COMPUTER-FLIGHT MANAGEMENT SYSTEM CONTROL AND DISPLAY UNIT may be exploited by ATC in routinely managing traffic. If this occurs, the unequipped aircraft might find itself at a relative disadvantage when approaching a busy terminal area since the ATC system might be designed to accommodate the equipped aircraft more effectively.

Because PNCs and FMSs are linked to the aircraft navigation systems, they have all the necessary hardware to make 4-D operations possible. The major reason that 4-D software has not been developed to any great degree is that the current ATC system is not designed to use this capability in carrying out its air traffic control responsibilities. Avionics managers will have adequate incentive to upgrade their software if and when this situation changes. Nevertheless, many of the systems have the capability of programming in crossing altitude constraints, feeder fix altitudes, drift down descents, and other nonstandard flight trajectories necessitated by ATC expediency. The relatively simple PDC or PMS, since it would always be flying "blind," would have little or no capability to choose the best profile subject to the ATC constraints of the day. Such flexibility comes at a price: PNCs and FMSs cost about twice as much to procure, install, and maintain as a PDC or PMS. Costs are the subject of the next section.

2.6 APPROXIMATE SYSTEM COSTS

Initial costs of procuring and installing a flight management computer system on an air carrier aircraft range from about $100,000 for an austere PDC to $250,000 for a full-capability FMS. Costs are summarized in Table 2-1.

Table 2-1. APPROXIMATE SYSTEM COSTS

PDC Hardware	$ 75,000 - $100,000
Installation, Maintenance, Training (provided by airline)	$ 25,000 - $ 75,000
Coupling to Navigation System	(Optional) - $ 75,000
Total Cost	$100,000 - $250,000 per aircraft
Anticipated Fuel Savings	2 to 6 percent $50,000 to $150,000 per year (depending on aircraft type and hours flown)
Anticipated Pay-Back Period	3/4 to 1 1/2 years for wide-body aircraft 1 to 2 years for 727s 1 1/2 to 3 years for DC-9s and other small air carrier aircraft 2 1/2 years and up for commuter and business aircraft

The share of this cost for PDC or PMS computer hardware alone is $75,000 to $100,000. This would include software tailored to the aircraft type on which the system would be installed. Installation and training are provided by the purchasing airline in most cases and are assumed to cost an additional $25,000 to $75,000 per aircraft. This cost would include installation of interfaces to the air data computer and other aircraft instruments. Autopilot and autothrottles can be coupled for little additional cost. However, a supplemental type certificate (STC) for the coupling arrangement must be obtained, which can be quite costly. Generally, the burden for obtaining the STC falls on the manufacturer, for whom the STC is a strong marketing plus. However, there is nothing to prevent the buyer from obtaining it, and this has happened in a few cases. The larger airlines may find it to be in their interest to expend the effort of obtaining an STC if it saves them from making avionics changes in a large number of airplanes.

If the FMC system is to be coupled to the on-board navigation system, a relatively complex computer-to-computer interface will be required. Furthermore, since much more data input flexibility will be required by the pilot, a more elaborate control and display unit (CDU) will be needed. These enhancements for a PNC or FMS are expected to cost up to $75,000.

Avionics manufacturers claim fuel savings in flight tests range from 2 to 6 percent of trip fuel, depending on the aircraft type, pilot proficiency in following fuel conservation procedures, typical stage lengths, and sophistication of the FMC. Depending on the daily utilization of each airplane, the 2 percent fuel savings yields an annual dollar saving ranging from $50,000 for 727s and similar aircraft to $150,000 for wide-body aircraft. If the claims are accurate, a typical payback period for this equipment would be one and a half years, although it can be considerably more or less depending on the aircraft size. That short a payback period would justify the investment.

2.7 PERCENT OF AIRCRAFT TO BE EQUIPPED BETWEEN 1980 and 1990

The percentage of aircraft expected to be equipped with some type of flight management computer will vary by aircraft type. The cost of a particular FMC model will be about the same whether the unit is installed in a four-seat general aviation aircraft or a 400-seat 747. However, the fuel benefits will be orders of magnitude greater for the 747. Fuel benefits accrued from an FMC will also increase with utilization of the aircraft. At present, scheduled air carrier aircraft are utilized at a much higher rate than air taxi, charter, corporate, or personal aircraft. Thus, the class of aircraft for which the payback period on an FMC would be shortest is the group of heavily utilized wide-body aircraft flown by the scheduled trunk carriers.

The age of a particular airplane will also be a factor in the decision whether or not to equip it with an FMC. An airplane near the end of its useful life is less likely to be equipped with one because it will have a shorter remaining useful life in which to recoup the investment. Consequently, there is little chance that aircraft such as the 707, 727-100, BAC-111, or DC-9-10 will have FMCs installed. Aircraft that have been re-engined to improve their noise performance and fuel efficiency, such as the DC-8-60 series, may be expected to remain in service for several more years and therefore are better candidates for being so equipped.

Another consideration is the extent to which ATC limits potential FMC savings. Airlines whose activity centers in the high density Northeast corridor may find that ATC restrictions and traffic delays prevent them from realizing significant savings from an FMC. Airlines operating similar equipment over similar stage lengths in some other region of the country may not suffer the same handicaps. Also, trunk airlines tend to run longer stage lengths and therefore longer cruise segments than regional airlines. Since the airlines can usually get the altitude and speed they want in the cruise segment of their flights, trunk airlines stand to derive more benefits from FMCs than local service airlines.

Financing an investment of $100,000 to $250,000 per airplane is not a serious problem for the trunk and major regional carriers. While most of them have a perennial cash flow problem, all have several options available for raising the money if they believe a fast payback is probable. Smaller carriers tend to be less able to finance such installations. An investment of that magnitude, even if economically justified, might stretch their available resources too thin. Smaller carriers also tend to operate smaller aircraft, for which the payback is not as fast. Corporate fleet managers may have less difficulty financing avionics purchases since they can draw from the resources of an entire large corporation. Even if the purchase of a piece of equipment cannot be economically justified, it may be justified on the basis of increased safety or comfort for the executives who fly on the aircraft. As a result, business aircraft are among the first to equip with new technology avionics.

It is expected that in all new aircraft as large as the 727 or larger, an FMC will be offered as a standard option. Installation costs for an FMC at the factory should be much lower than those for a retrofit because of the number and complexity of the interfaces required. Furthermore, certification would already have been provided for a factory installation, while a retrofit might require a supplemental type certificate. This is another reason why installing an FMC in a new airplane is a more attractive investment than retrofitting one into an older airplane.

A PDC is currently offered for new 737-200s but not presently for DC-9s. New aircraft with less than 100 seats are probably not good candidates for FMCs at current fuel and equipment prices. Of course, further real increases in fuel prices or decreases in FMC cost could change a marginal investment into a good one.

In the retrofit market, it is assumed that all retrofits will take place by 1985. If the payback period is good enough now, there is no reason to postpone retrofitting except for financing or logistics problems. It may take carriers with large fleets as long as five years to rotate all their airplanes in to be equipped. Any aircraft not retrofitted by 1985 will probably be too old to justify the action. Because of their higher payoff, wide-body aircraft will be equipped first. Retrofitting them is expected to be completed by 1983.

Forecast rates for equipping each aircraft type expected to be in use in the 1980s are shown in Table 2-2, both for new and older aircraft. Forecast rates are based on the assumptions outlined above. Implications on major hub traffic in the late 1980s and '90s will be discussed in Chapter Six.

Table 2-2. FORECAST PERCENT OF EQUIPPED AIRCRAFT, BY AIRCRAFT TYPE

Aircraft Type	Retrofit Percentage By Year					New Percentage	Comments
	1981	1982	1983	1984	1985		
707, all series	0	0	0	0	0	--	Being phased out of all operations
727-100	0	0	0	0	0	--	Too old; will be used only for charters, backup, extra sections after 1985
727-200	20	40	60	60	60	100	Payback adequate for new installations; marginal for retrofits
737-200	10	20	30	30	30	50	Marginal payback for both new and retrofit
747, all series	50	75	100	100	100	100	Conventional wide-body aircraft; DELCO system sold as standard on new aircraft
747-F							
DC-8, exc 60 series	0	0	0	0	0	--	Being phased out
DC-8, 60 series	10	30	50	50	50	--	About 50% of re-engined aircraft to be equipped
DC-9-10/20	0	0	0	0	0	--	Too old and too small for adequate payoff
DC-9-30/40	10	20	30	30	30	50	Similar to 737-200
DC-9-50	10	20	30	30	30	50	Similar to 737-200
DC-9-80	--	--	--	--	--	100	Modern all-digital aircraft to compete favorably with 727 and 757 in the 1980s
DC-10, all series	50	75	100	100	100	100	Conventional wide-body aircraft
BAC-111	0	0	0	0	0	--	Too old and small to be equipped
CV-580	0	0	0	0	0	--	Too old and small to be equipped
A-300	50	75	100	100	100	100	Modern wide-body will be equipped
A-310	--	--	--	--	--	100	Sperry FMS standard equipment
Falcon 20	0	0	0	0	0	0	Too small for adequate payoff
L-1011	50	75	100	100	100	100	Conventional wide-body aircraft; ARMA System sold as standard
L-1011-500	100	100	100	100	100	100	Modern, long-haul, wide-body aircraft; ARMA System sold as standard
757/767	--	--	--	--	--	100	Sperry FMS standard equipment
New All Cargo	--	--	--	--	--	50	Charter aircraft less likely to equip
New, under 120 seats	--	--	--	--	--	50	Marginal payback for small aircraft
New, 120-240 seats	--	--	--	--	--	100	Good payback for medium-load new technology aircraft
New, over 240 seats	--	--	--	--	--	100	Good payback for all wide-body aircraft

CHAPTER THREE

ENGINEERING DESIGN

3.1 INTRODUCTION

Chapter Two covered general capabilities and features of FMCs from the point of view of the pilot. This chapter looks at general characteristics of the engineering design. The emphasis is on system hardware and how it fits in with other flight deck avionics. The point of view is more that of a design or installation engineer. The FMC hardware is flexible enough to be capable of having a direct interface with ATC and possibly being exploited by ATC in conducting its routine business; a discussion of the issues surrounding that subject is also presented.

3.2 PDC SYSTEM ARCHITECTURE

The performance data computers marketed by the various manufacturers use off-the-shelf hardware supplied by semiconductor houses (Intel, Texas Instruments, etc.). Depending on the extent of the system capabilities, the computer will have 16 to 64K words of memory. PNCs and FMSs will typically require more memory than PDCs and PMSs in order to accommodate the navigation data. One manufacturer has provided for expandability to 128K words to handle the extensive route structures of the larger trunk carriers; the other PNC and FMS manufacturers provide for 200K words of offline disk storage or its equivalent for this purpose. In all FMCs, storage is a flexible resource that can be used to suit the needs of the purchasing carrier. Available storage can be filled with canned flight plans, navigation waypoint data, radio frequencies, arrival and departure data, or even fuel prices at various locations if tankering* is under consideration.

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*Tankering is the carrying of fuel as additional cargo. Normally, carriers load only enough fuel for each leg of a flight and refuel at each stop. Carrying fuel as cargo adds to the weight of the aircraft, which in turn increases the amount of fuel burned over the trip. The cost penalty is so severe that tankering is done only under two unusual circumstances: (1) fuel is unavailable at a destination, or (2) the price difference is so great that money can be saved by carrying the lower-priced fuel rather than buying it at a higher price. Ironically, tankering is more widespread when spot shortages of fuel develop. This causes extra fuel to be burned carrying extra fuel, exacerbating the shortage.

All systems use some quantity of read-only memory (ROM) to store software and aircraft parameters needed every time the system is used. Random access memory (RAM) is also required in processing: PDCs and PMSs need up to 4K, while PNCs and FMSs require at least 16K.

In navigation-equipped systems (PNCs and FMSs), updating the stored data bases of navigational waypoints and stored flight plans can be a serious problem. Route structures can change frequently, and the FMC must be kept up to date or it will become obsolete in a few months. The manufacturer of one system has come up with a novel solution to this problem. Its disk pack has enough capacity to hold two independent navigation data bases. The system is set up so that one base can be updated at some time during each month by means of a portable ground loader. At the end of the month, the pilot can switch from the old data base to the new. In this way, the individual units can be updated throughout the month instead of having to be done in a single day or having aircraft operating with different data bases.

Control and display units vary widely in design, capacity, and capability. There are CRT displays, plasma gas discharge displays, LED displays, and both 7-segment and 16-segment incandescent displays. Except for the incandescent displays, most systems use a 5 x 7 dot matrix for each character. Simmonds uses a small display separate from the CDU located in a prominent place in the cockpit for display of performance data; others set instrument bugs directly.

Instruction cycle times for FMCs are 1 to 4 microseconds. While this is as fast as is currently available, the length of time required necessitates some computational compromises in calculating the profiles. Functional cycle times for recalculating the best altitude, airspeed, etc., range from 5 to 30 seconds. Data relating to flight management well downrange (say 200 miles or more) are assigned the lowest priority and may be recalculated only every few minutes. Highest priority is given to reading instruments and operating the autopilot and autothrottle: this is done every 100 milliseconds in all PMSs and FMSs. All other computer functions, such as updating the CDU, adjusting radio tuning, updating position and fuel performance, and handling ad-hoc requests from the pilot, are done on a 1 to 2 second cycle.

Most of the hardware for air carrier FMCs (other than the CDUs) is stored in the airplane's avionics bay. Sizes range from 1/2 to 1 ATR (a standard unit of size) and weights from 25 to 50 pounds. Power consumption is from 100 to 300 watts. The additional weight and power drain detract from potential operational savings, but not very much. A more serious consideration is the lack of cockpit space for the CDUs and other displays. Particularly in smaller jets such as the DC-9 where space is at a premium, installation of an FMC may require something else to be taken out. Manufacturers of the FMCs indicate that the increases in efficiency resulting from use of an FMC would justify making such changes.

3.3 FLIGHT DECK CONFIGURATION

In the cockpit, the major visible sign of the FMC is the CDU. Figure 3-1 is a photograph of an installed ARMA flight management system with a map display. This particular configuration is for an L-1011-500 aircraft. The dual CDUs and map display are installed in the console just above the throttles, which are partially visible on the left side of the picture.

The CDUs are positioned so that the flight engineer can see them simply by looking over his left shoulder, although it might be awkward for him to reach the keyboard. In this picture, both CDUs have the same information displayed. However, all of the systems with dual CDUs allow queries from either keyboard independently.

Invisible to the flight crew are the large number of data interfaces needed by the FMC in the course of computation. The air data computer provides airspeed, altitude, temperature, etc., corrected for the current flight environment. The computer is aware of the aircraft configuration (gear, flaps) and air bleeds required (for air conditioning, pressurization, and de-icing). It also has access to performance data for each engine. For PNCs and FMSs, the navigation computer provides position, heading, planned flight path, and winds aloft. The pilot is expected to enter field elevation, gross weight, fuel weight, and other cost factors. As the flight progresses, he will need to enter ATC speed and altitude constraints. If he has time, he can enter forecasts of wind and temperature downrange to improve the flight profile further.

The PDC will, in turn, drive several cockpit instruments and controls. The primary monitor for the flight management computer is, of course, the CDU. The computer can also set bugs on the EPR and airspeed indicators and drive flight mode annunciators, autothrottle and autopilot systems, and horizontal situation indicators (HSI). Advanced FMCs may have an auxiliary map display instead of or in addition to the HSIs.

Figure 3-2 shows an installation of a fully coupled flight management system. The performance computer is represented by the box at the lower right corner of the diagram. It contains data on aircraft dynamics, performance limits, and algorithms for generating flight profiles. The navigation computer contains the flight plan and knows the position of the aircraft. It has access to a data base of VOR and DME waypoints and canned flight plans. The navigation data base may be updated off-line by use of a portable carry-on loader. Both the performance computer and the navigation computer have access to the information in the air data computer, which is processed from raw input from the various sensors.

3.4 FLIGHT MANAGEMENT COMPUTER LIMITATIONS

The capabilities of flight management computers are limited by cost factors, existing technology constraints, and user operational contraints. This section describes some of the problems with currently available FMCs.

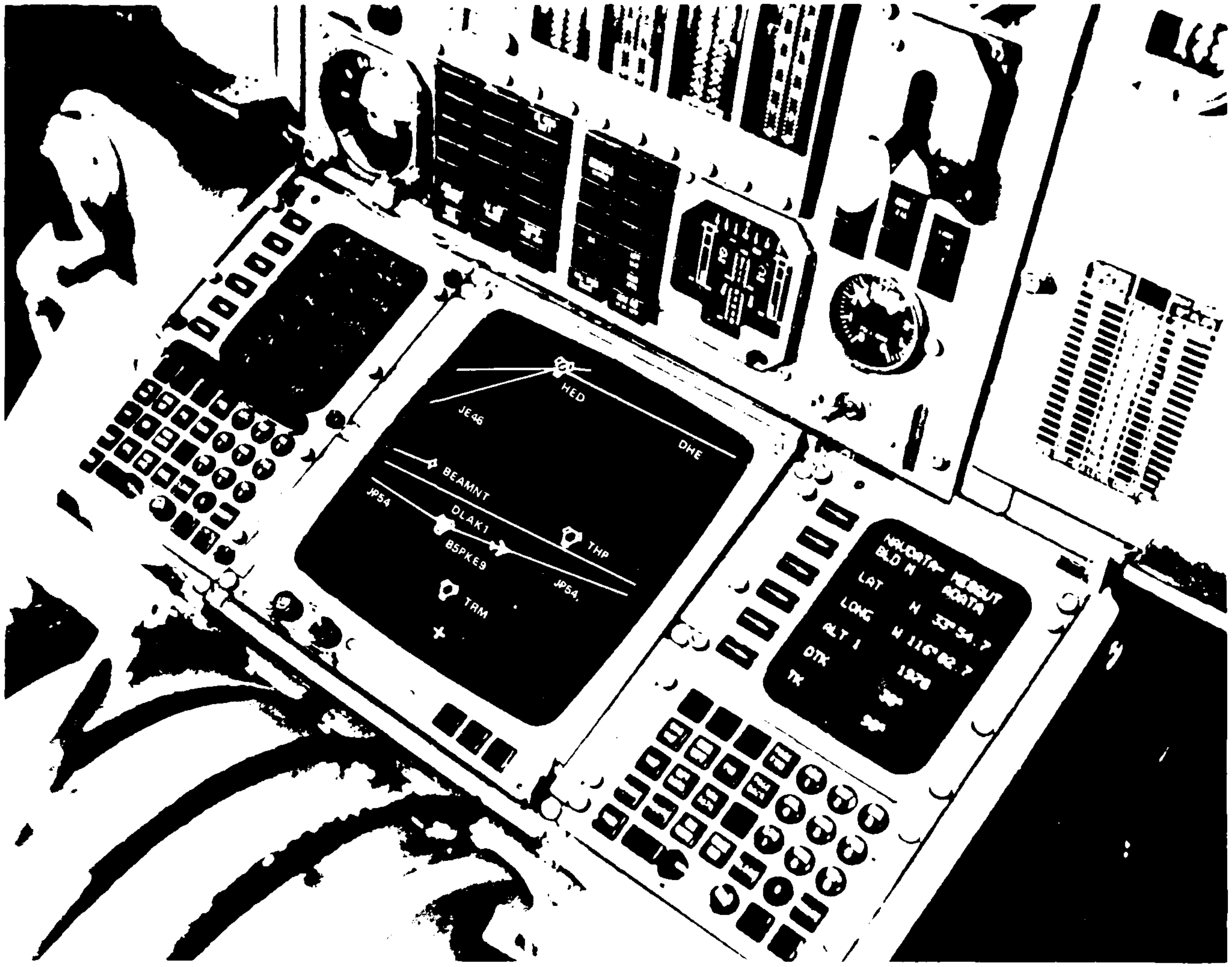
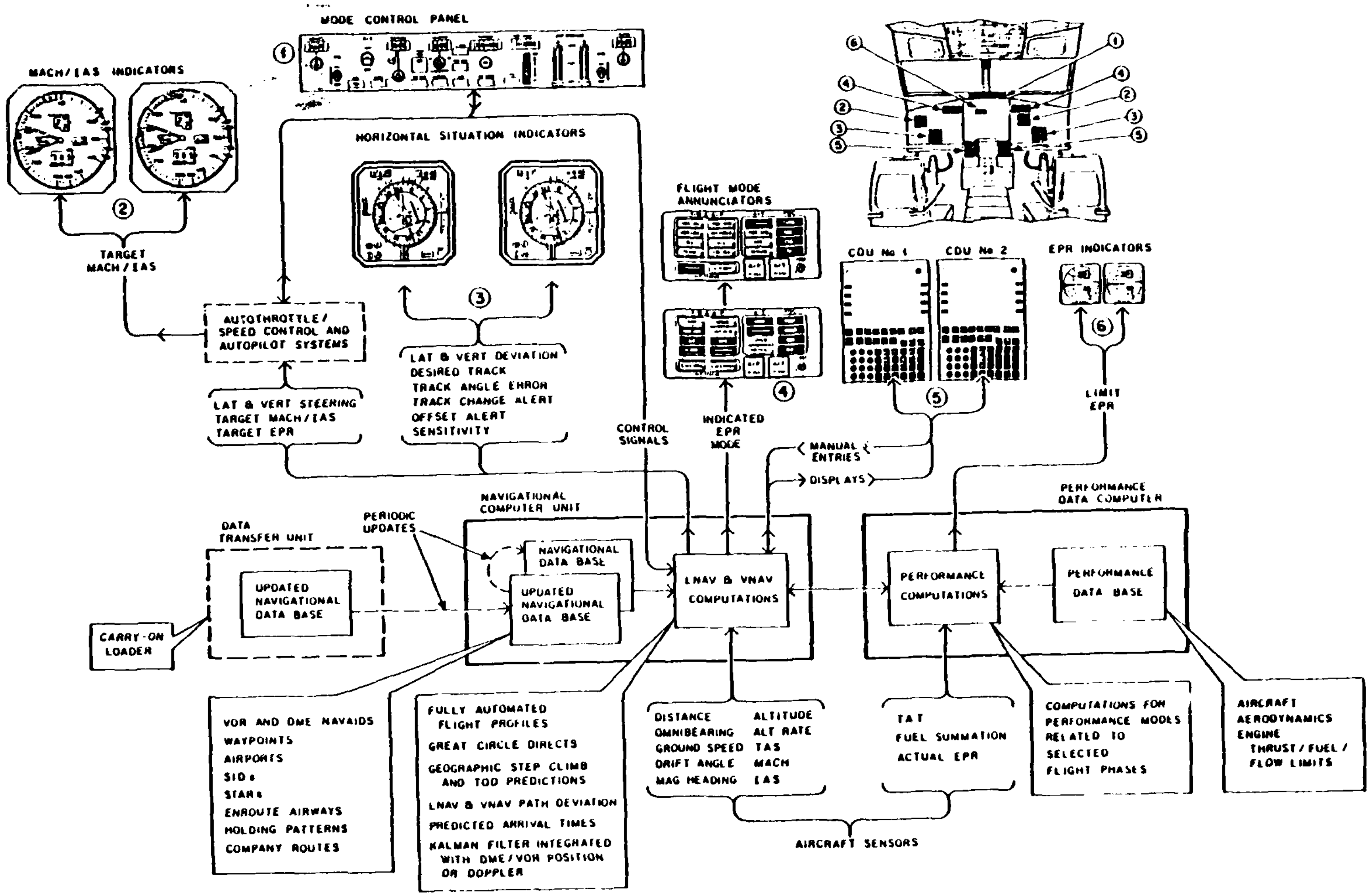


Figure 3-1. FMS DUAL CDUs WITH MAP DISPLAY

(Courtesy of ARMA division of AMBAC Industries, Inc.)



(Reprinted with permission of Lear Siegler, Inc.)

Figure 3-2. FMS INSTALLATION BLOCK DIAGRAM

Flight management computers are not designed for detailed flight route planning. That function is typically done on the ground by means of an airline flight planning computer. It would be difficult for an on-board unit to perform this function because of the need for an extensive winds-aloft data base. When an aircraft in flight is forced to make a significant course correction, the FMC cannot generate a new optimal route -- the pilot must decide whether to fly back to the original course or request a new one. Airline dispatch personnel, using ground-based flight planning resources, assist the pilot in making decisions of this type.

FMCs have limited ability to handle ATC-imposed constraints or delays. If ATC cannot clear the optimum altitude or speed, the pilot will find it difficult to obtain the best alternative from the FMC. If a delay is imposed, the FMCs provide little information as to how to consume the delay in the most fuel-efficient manner, although most units will provide the speed which minimizes fuel consumption per hour (best hold speed). Some of the more flexible FMSs allow the pilot to enter "at or above" constraints for climb and descent.

Another problem is the difficulty of customizing software for the specific airplane on which the equipment is installed. Drag does vary among different airplanes of the same type, and such variations can produce measurable differences in fuel consumption, but the cost of quantifying these variations will almost surely exceed any benefits from an accurate measurement of airframe parameters. Similarly, thrust varies among engines of the same type. Age, maintenance, and manufacturing variations can cause a substantial difference in thrust output from apparently identical engines.

A final limit to the usefulness of FMCs results from the lack of 4-D software in the current models. While PNCs and FMSs have most of the hardware necessary to make 4-D navigation work, the software for currently available systems does not have this capability. The ability of aircraft to arrive at a particular position and altitude at a specified time might be useful to ATC, particularly in sequencing aircraft for landing. In some sense, this is a chicken-and-egg type of problem, since the FAA has no incentive to explore the benefits of 4-D based ATC if there is little or no 4-D capability in the field, and the airlines have no incentive to develop 4-D software if the FAA cannot accommodate it. Another major obstacle to making 4-D viable is the difficulty of providing the FMC with information about winds aloft between its current position and the 4-D waypoint. Without this information, it would be difficult to avoid large, fuel-costly power changes required to correct deviations in the planned flight trajectory. Getting wind data to the aircraft would probably be best accomplished by way of a data link. These issues will be discussed further in Section 3.5 and in Chapter 6.

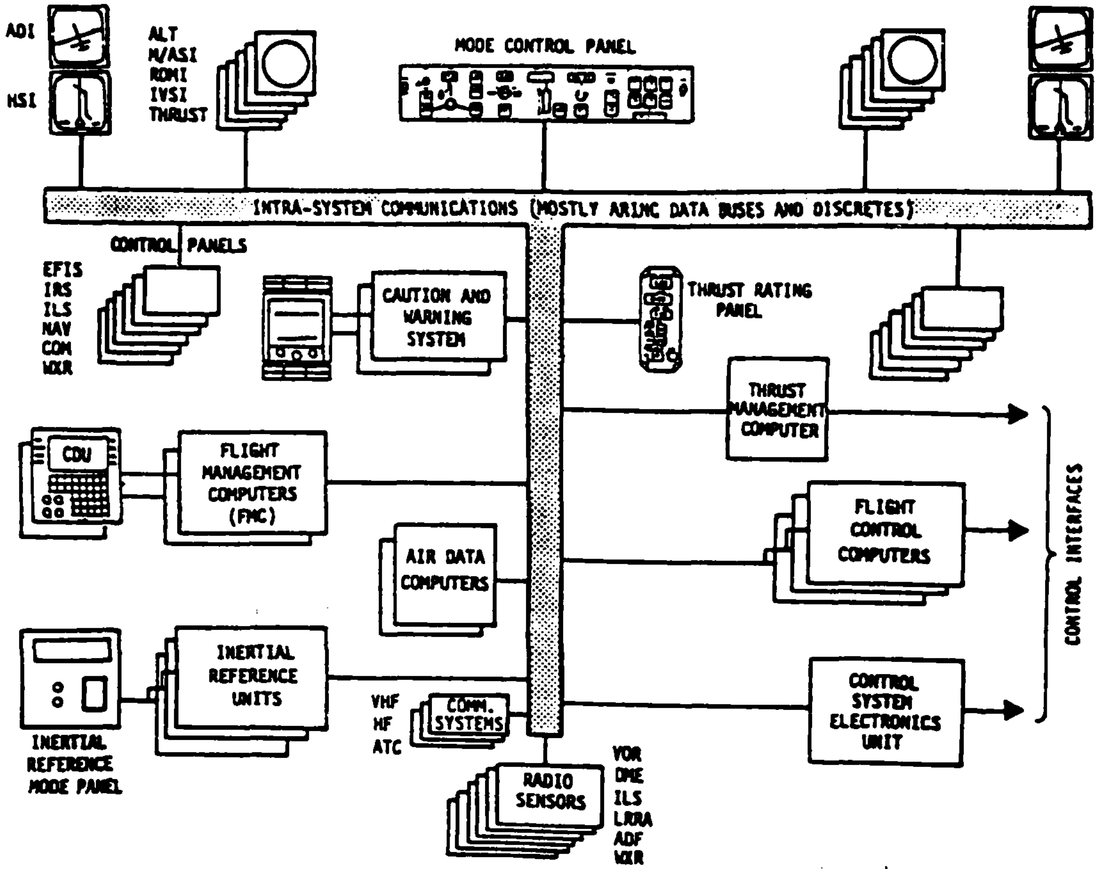
3.5 INTEGRATION OF FMCs WITH OTHER COCKPIT AVIONICS

The presence of an on-board computing capability and the almost unlimited flexibility of computer-driven displays raise the issue of whether the FMC could be (or ought to be) extended to control various other cockpit avionic systems. Through interfaces with the air data computer and other sensors, the FMC already knows a great deal about what is going on in the flight. Most PDCs have some capability to monitor various aircraft support systems and issue warnings about any problems. Where multiple sensors exist for a particular item (e.g., total air temperature), independent readings can be compared and validated; if the readings are unusual, a warning message is shown on the control and display unit. FMCs monitor the engines, the use of bleed air, and almost all output from the air data computer. Most manufacturers have shied away from the idea of making the PDC the aircraft watchdog. That is, they do not want to design it to issue warnings, for example, that icing conditions do not exist and therefore the de-icing equipment should be turned off. Not only would the capability to perform such a function to any degree of thoroughness require the calculation of a large number of logic trees but it would put the FMC manufacturer into the undesirable business of second-guessing what might have been a calculated judgment by the pilot.

FMC manufacturers will have a very difficult time selling computers for retrofit if an installation requires a major overhaul of other cockpit avionics. Modularity of the FMC is one of the most important keys to retrofit sales success. Fuel savings notwithstanding, no airline could afford the acquisition, maintenance, and training costs that would result from designing the cockpit around the FMC for an aircraft already in service. The FMC can take data from some instruments and drive others, but it will not change the basic cockpit configuration. For retrofits, therefore, the flight management computer must be a stand-alone system. Chances of integration with other avionics are slight.

The above reasoning does not apply at all to the design of avionics for the latest generation of air transports, since the airlines automatically commit themselves to an extensive maintenance and training program simply by adding a new aircraft type to their fleet. Under those circumstances, it makes sense to design the cockpit from the beginning. Figure 3-3 shows a simple block diagram of the 757/767 flight management system. Several separate computer subsystems receive their inputs from sensors or other computers and provide outputs that drive other computers or displays. The all-digital interfaces eliminate the problem of analog-to-digital conversions for older instruments not designed to link to a computer.

In addition to the CDU for the flight management computer, the 757/767 cockpit will have electronic CRT displays that will replace the mechanical attitude director indicator (ADI) and horizontal situation indicator (HSI) used on conventional transports. Figure 3-4 shows a possible EADI presentation. This unit shows all the usual information such as pitch and roll and instrument landing system (ILS) localizer and glideslope. There is some flexibility to include other information (in the corners) or to change scale sensitivities. To minimize human factors problems, the display was designed to look as much as possible like a conventional ADI.

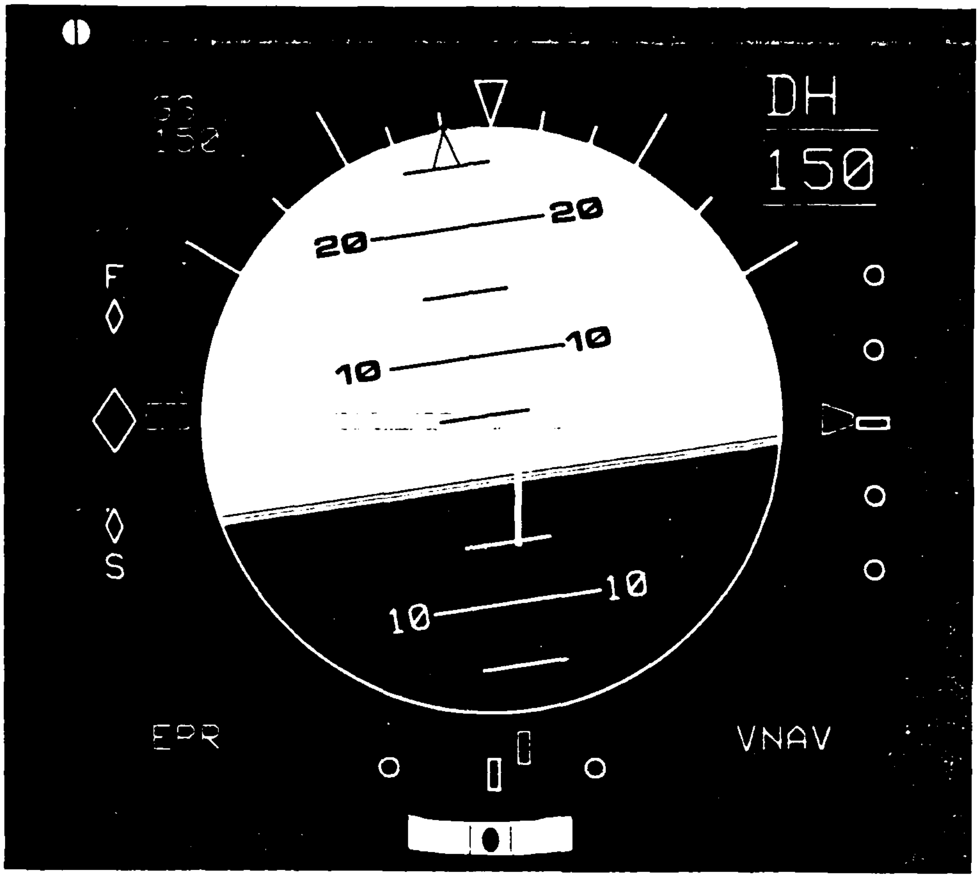


(Reprinted with permission of Boeing Commercial Airplane Company)

Figure 3-3. 757/767 FLIGHT MANAGEMENT SYSTEM MAIN ELEMENTS

The EHSI display was also designed to look like conventional HSIs. However, the EHSI has a number of additional capabilities, the most elegant of which is to show a simple map of the flight path immediately ahead. An example is shown in Figure 3-5. Weather data from the weather radar are superimposed on the map and appear as the blob on the left half of the display. Hazardous weather is coded red; lighter rain is shown in green. The display is updated every 50 milliseconds. Besides the map mode shown in the figure, other modes show compass display, VOR or ILS intercept, and en-route flight planning.

A third display system for the 757/767 is the engine indication and crew alerting system (EICAS). This comprehensive crew warning system encompasses all the major aural safety warnings currently required, such as stall, overthrust, terrain proximity, engine fire, lack of gear or flaps when needed, or pressurization failure. These are major flight emergencies that demand immediate attention. The system will also issue cautions for conditions that the crew must be aware of and eventually correct. The type of condition covered by a caution would be, in effect, a "slow emergency."



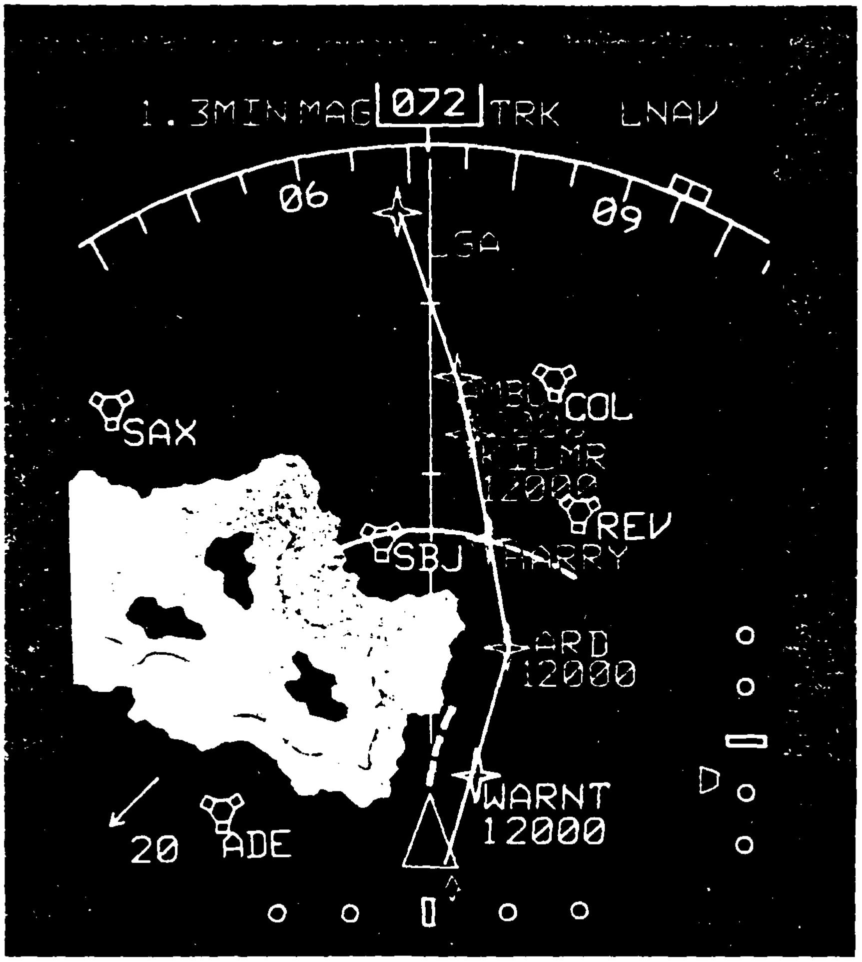
(Courtesy of Collins Air Transport Division)

Figure 3-4. SAMPLE EADI DISPLAY IN 757/767

Advisories will be issued for conditions that are unusual but are not life-threatening. The designer must be careful to define advisory conditions narrowly enough that the system will not be continually distracting crew attention with nuisance warnings. Too loose a criterion will result in the watchdog situation described previously, in which the crew might discount or ignore EICAS messages because there are too many.

3.6 SUITABILITY OF INTEGRATED AVIONICS FOR ATC PURPOSES

Many of the capabilities of flight management computers and other advanced avionics could help ATC, either by reducing controller workload or by providing the controller with information about the flight environment he could otherwise get only by asking the pilot. The application that has received particular attention from the FAA and the airlines is 4-D navigation, which is the subject of Chapter Six. Other potential applications could be implemented independently of 4-D and are discussed in this section.



(Courtesy of Collins Air Transport Division)

Figure 3-5. SAMPLE EHSI DISPLAY

Much of the data gathered for use by the FMC could be useful to ground ATC. Communicating this information over air-ground voice channels from pilot to controller is obviously impractical: some type of data link would be required. The ARINC Communications Addressing and Reporting System (ACARS) is a commercially available data link that could be used for this purpose. A Discrete Address Beacon System (DABS) data link, when it becomes operational, would also do the job. Ultimately, both systems will be used for transmission of flight data. The advantage of ACARS is that it is currently available with excellent coverage; the advantage of DABS is that it will be under the management of FAA and therefore will be made available to everyone.

ACARS is currently used primarily to report block-to-block times to company dispatchers. One airline (American) plans to use ACARS to transmit winds-aloft data from wide-body aircraft every 3.75 minutes of flight. When this system is fully operational, aircraft can receive the most recent winds-aloft observations reported by the last aircraft to pass through the same area. Those observations can supplement or supercede the airlines' own winds-aloft forecasts. American is interested in having other airlines do the same thing and sharing the wind data, and some are considering the proposal. However, most airlines, including those already using ACARS, could not justify the added expense of such a system for their own route structures alone and are therefore not pursuing this too vigorously. Furthermore, some airlines expect that the FAA will someday provide a real-time winds-aloft data base once DABS is operational, and until then, they are willing to do without that service.

Both the airlines and the FAA see value in an aircraft being able to transmit its desired flight profile by data link to an ATC computer, which could in turn project the profile ahead in time, observe conflicts with other traffic, and assign waypoint slot times. Alternatively, the on-board computer could request a slot time from ATC, which would then assign one as close as possible to the desired time. This dialogue could be designed to take place without any human action. There are limits to how far this can be taken, however. The technology will soon exist for ATC computers to transmit real-time control commands to the FMC by data link, but neither the FAA nor the airlines are ready to delegate their flight responsibilities to a computer. Difficult-to-answer questions of software reliability will keep human controllers and human pilots solidly in the loop for the foreseeable future.

It seems clear that major exploitation of flight management computer capabilities by ATC will have to wait for the successor to the 9020 computer. While there is much information that could be useful to ATC, present computers do not have the capacity to use it. Much of the set of useful data is already maintained on the flight strips the controllers use. However, to assure that the forward projections of flight profiles are accurate and that the aircraft can meet their slot times within a few seconds (if such accuracy is necessary) will require not only developing ground computer capacity, but also equipping the majority of air carrier aircraft with 4-D capability. While the benefits of such a system are worth investigating, so many additional capabilities will be required both in the air and on the ground that this type of system could not evolve before 1990.

CHAPTER FOUR

FLIGHT PROFILE MANAGEMENT IN CLIMB AND CRUISE

4.1 INTRODUCTION

The preceding two chapters have discussed the general capabilities of flight management computers from both a user's and a designer's standpoint. However, the issue of greatest concern to the FAA is the potential impact of FMCs on the ATC system. While there are substantial differences in capability and complexity among the FMC models currently being produced, all help to operate an aircraft in an efficient manner. Therefore, the key to understanding how FMCs might affect the ATC system is to understand what is involved in efficient aircraft operations. A number of initializing factors must be considered (e.g., aircraft type, takeoff weight, trip length) in calculating the optimum operational parameters (e.g., rate of climb, airspeed, cruise altitude, descent profile).

The next two chapters present the typical trade-offs that must be made to achieve efficient flight operations--trade-offs that are typically computed by FMCs. This chapter covers issues for climb and cruise: Chapter Five is devoted to descent and approach issues. As a baseline, flight profiles assume a single airplane in the sky, unburdened by any ATC restrictions. The effect on airline costs of certain routine ATC constraints, such as flight level separation, is then assessed. The purpose of this analysis is not to evaluate the necessity of the restrictions but rather to document the savings that could be achieved if there were no such restrictions. Finally, where an aircraft must fly a significant distance off its optimal profile, for whatever reason, the cost of doing so is calculated and presented.

4.2 FUEL-OPTIMAL VERSUS COST-OPTIMAL PROFILES

Air carrier direct operating costs have four major components: fuel, crew, maintenance, and depreciation. Although fuel is the dominant factor, representing 50 to 60 percent of direct costs at current prices, optimizing flight profiles on the basis of fuel costs alone will not minimize total cost.

The flight profiles planned for use in normal air carrier operations are generally slightly faster and one to two percent less fuel efficient than the fuel-optimal profiles. The reason for this is that the other three cost factors (crew, maintenance, and depreciation) are related to time in flight. Flight crews are allotted a maximum flight time every month, and every minute spent on the aircraft with engines running counts toward that allotment, even if the aircraft is merely taxiing. Routine maintenance is usually based on engine hours also. Depreciation costs can also be considered time-related since the resale value of the aircraft decreases fairly uniformly as its duty hours increase.

Thus, direct operating costs can be modeled as having a time-cost component and a fuel-cost component. Pilots have the option of trading off fuel for speed, as for example, when a flight is running late, and many of the passengers have connecting flights to catch. If they miss their connections, they may have to complete their trips on a different airline; they might avoid future trips on the late carrier as well. Under these circumstances, the pilot might choose to burn extra fuel to make up some time. On the other hand, the pilot of a flight operating late at night might choose to slow down to a speed closer to the fuel-optimal speed, since few passengers can be expected to be on a tight schedule.

For cruise flight at a particular altitude and aircraft weight, the performance charts give a number of optimum speeds. "Maximum range cruise" speed (or simply, "max range") is the speed that maximizes nautical miles per pound of fuel. This speed (or slower) is flown only in the event of very strong tailwinds or a tight fuel situation. New wide-body jets often have stability and control problems associated with flying at the max range airspeed. The speed at which fuel consumption is 1 percent worse than maximum range speed is designated "long range cruise" (LRC). This speed is usually three to six percent faster than the maximum range speed. It represents a significant, yet conservative trade-off of fuel for speed. Most carriers today operate slightly faster than long range cruise: the LRC speed would be economically justified if fuel costs were 75 to 80 percent of direct operating costs instead of the 50 to 60 percent they are now. The "max range" and "long range" designators are also used to characterize climb and descent profiles, with the same fuel implications.

For the purpose of this study, profiles designated as optimal are minimum-cost profiles unless otherwise indicated. As such, it is likely that a profile designated as minimum-<u>cost</u> is not the most <u>fuel</u>-efficient that could be flown; however, the value of time lost from flying a minimum-fuel profile would outweigh the fuel savings. In spite of the dominance of fuel costs in overall direct operating costs, the time factor is still very important to the airlines. If aircraft slow down to the slow fuel-optimal speeds, the duty hours necessary to travel the same routes must increase. To make up for this lost time, an airline would have to cut ground servicing time, thereby putting pressure on on-time performance, or adjust the schedule to reflect the change in flight times, and perhaps lose a flight per day on some aircraft. There is a trade-off that goes beyond the pressures to fly as fast as the competition.

Most of the analysis in Chapters Four and Five is based on a fuel-burn model currently under development by the FAA Office of Environment and Energy. Additional documentation on this model and how it was used is given in Appendix B. Table 4-1 shows the assumptions used for various aircraft. Time costs were obtained from Reference 12 of the Bibliography. An "empty" aircraft consists of the airframe, crew, no passengers, no cargo, and minimum fuel reserves. A "full" aircraft is assumed to have a full passenger load with additional fuel and cargo. The full airplane weight is a typical full-load landing weight and is slightly less than the maximum landing weight of the aircraft. The full weight as shown in Table 4-1 is up to 30 percent less than the maximum take-off weight of the aircraft.

Table 4-1. AIRCRAFT STATISTICS USED IN ANALYSIS

Aircraft Type	Time Cost (Dollars per Minute)	Fuel Cost (Dollars per Pound)	Long Range Cruise Mach	Gross Weight (Pounds)	
				Empty	Full
DC-9	7.92	0.126	0.762	62,000	82,000
727	13.75	0.126	0.789	108,000	160,000
A-300	22.00	0.126	0.777	190,000	270,000
L-1011	30.00	0.126	0.829	250,000	350,000
DC-10	27.50	0.126	0.826	260,000	380,000
747	35.00	0.126	0.840	400,000	550,000

4.3 UNRESTRICTED FLIGHT PROFILES

The minimum-cost management of an aircraft trajectory through airspace is a complex optimal control problem. In the 2-D case (downrange distance and altitude) pilots have two controls to work with: thrust and pitch. By adjusting the throttle, the pilot can control the amount of thrust from idle levels to full. Maximum thrust available decreases with altitude for all air-breathing engines, and this limits the service ceiling. Thrust can be used to increase the kinetic energy of the aircraft (speed), increase the potential energy of the aircraft (altitude), or overcome drag by propelling the airplane downrange. Because the amount of available thrust energy is limited, an increase of one of these categories necessarily implies a decrease in the others.

A diagram of an ideal flight profile appears in Figure 4-1. A departing aircraft accelerates on the ground at takeoff thrust to rotation speed and lifts off, initially at a high angle of attack. It climbs to a relatively secure altitude, and then reduces pitch in order to accelerate to climb speed, usually 300 to 330 KIAS. Flaps are retracted during the acceleration as speed increases to the point where they are no longer needed. If terrain conditions permitted, it would be cost effective (but unsafe) to go into a little dive to achieve climb airspeed as fast as possible. In practice, however, carriers climb to about 3,000 feet, then accelerate only to 250 KIAS because of the speed limit. At 10,000 feet they reduce pitch again and accelerate to climb speed. Since this profile assumes no ATC constraints, acceleration is done at low altitude and occupies the first 10 miles of the flight.

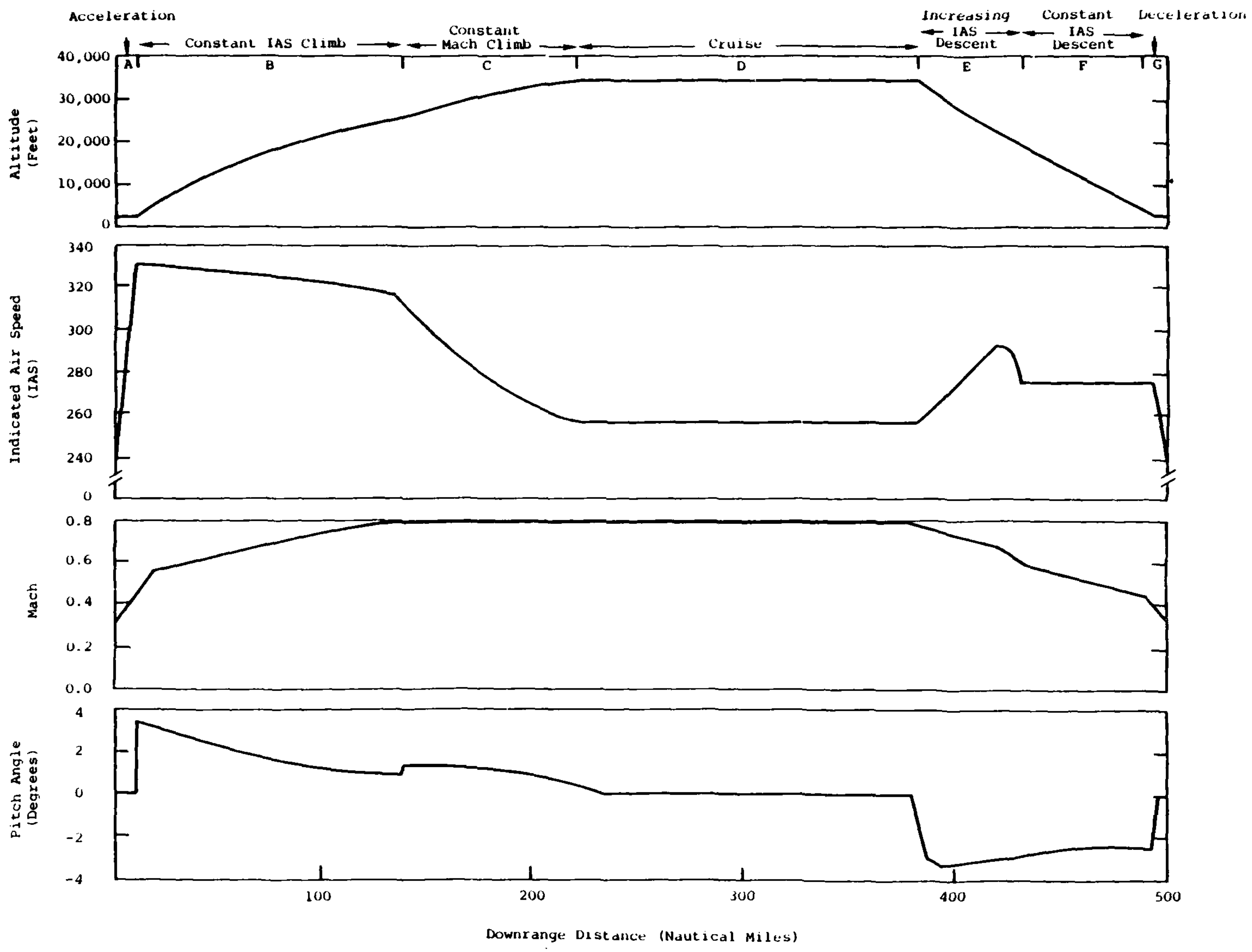


Figure 4-1. SAMPLE UNRESTRICTED 500-NAUTICAL-MILE FLIGHT PROFILE

Optimal climb is conducted at a slowly changing IAS and pitch angle. As the aircraft climbs, the decreasing air density causes a drop in maximum thrust output. As a result, the best climb airspeed drops about 20 knots between 10,000 and 30,000 feet, and the pitch angle drops as well (Region B). At some point before the end of the climb the aircraft will reach its cruise mach. The pilot will increase pitch slightly to maintain a constant mach climb (Region C). As the climb continues, IAS, pitch angle, and thrust drop, even though the aircraft is maintaining maximum climb power. Aircraft are capable of much faster and steeper rates of climb than these figures suggest. However, steeper climbs convert more of the thrust into potential energy (altitude) than into kinetic energy (speed). Thus, the aircraft makes less down-range headway.

When the aircraft reaches its optimal cruise altitude (based on weight), the climb ends and cruise begins (Region D). Pitch is reduced to near zero and throttle to about 70 percent of maximum power. This maintains a constant mach speed. As fuel is burned off, the optimal altitude increases by 10 to 15 feet per minute. Since the cruise segment in this flight is only about 20 minutes long, the slow climb is not apparent in the graph.

The cruise phase continues until the aircraft is near enough the destination airfield to begin descent, about 120 miles in this case. Throttle is reduced to idle and the nose lowered to effect a descent. Indicated airspeed initially increases until an optimal descent value is reached (Region E). The pilot then maintains the descent at idle thrust and constant IAS all the way down (Region F). At final approach altitude, the aircraft is leveled to allow excess speed to bleed off (Region G). Below about 210 KIAS, flaps must be added to maintain lift through the approach and landing.

4.4 EFFECT OF THE 250 KIAS LIMIT BELOW 10,000 FEET

For safety reasons 250 KIAS is the maximum speed permitted below 10,000 feet MSL. This affects flight profiles both in climb and descent. Figure 4-2 shows the effect of this restriction.

During climb, the airplane accelerates only to 250 knots and is therefore able to begin climb sooner and at a steeper angle (point A). However, at 10,000 feet it must level again to accelerate to normal climb speed (point B). From this point the climb profile is the same as in the unrestricted case, but several miles uprange. The airplane will therefore reach cruise altitude sooner (point C).

In descent, 250 knots is close to the maximum lift/drag speed. Airlines usually descend at 300 KIAS or greater; the time saved by doing so more than compensates for the additional fuel consumed. Thus, the aircraft will begin descending earlier (point D), decelerate to 250 knots at 10,000 feet (point E) and then resume the descent at a shallower angle (point F). In descent, the 250 KIAS limit forces carriers to save fuel, since they would be unwilling to descend so slowly without that restriction. However, the total cost is greater due to the increased crew, maintenance, and depreciation costs associated with these slower speeds.

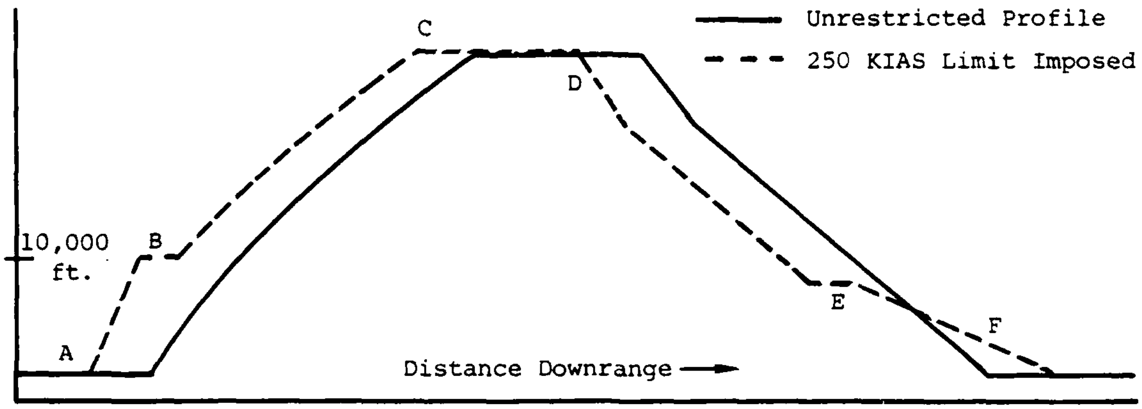


Figure 4-2. ALTITUDE PROFILE WITH AND WITHOUT THE 250 KIAS LIMIT (GREATLY EXAGGERATED)

Table 4-2 summarizes the effect of the 250 KIAS limit on the fuel consumption of a 727-200. The restriction costs fuel in climb and saves it in descent. Some time is lost in each phase. The speed limit has very little effect on cruise: it causes a slight shift in the points at which cruise starts and ends. The minor effects due to the shift have been included in the climb and descent statistics. At current values for fuel and time, the limit costs the airlines an additional $22.70 per flight. Other air carrier aircraft experience a cost proportionate to their size. It is significant that virtually all this cost is incurred in the climb phase of flight. As will be seen in the next chapter, descent costs are relatively insensitive to descent speeds.

Table 4-2. EFFECT ON COST OF 250-KIAS LIMIT

Flight Segment	Additional Fuel Burned (Pounds)	Additional Time (Minutes)	Additional Cost
Climb	+65	0.6	$16.44
Descent	-114	1.5	$ 6.26
Overall	-49	2.1	$22.70

Basis of calculations
- Aircraft - 727-200
- Takeoff Weight - 160,000 pounds
- Time Cost - $13.75 per minute
- Fuel Cost - $00.126 per pound

4.5 OTHER FACTORS AFFECTING CLIMB PROFILES

4.5.1 Engine Thrust Variations

As pointed out previously, the minimum-cost profile depends not only on the lift/drag characteristics of the airframe but also on the thrust/drag characteristics of the engines. Two models of the same aircraft type fitted with different engine models are, for these calculations, two different aircraft types. If lift and drag are the same on the two airplanes, then differences in performance are primarily dependent on differences in thrust output of the engines.

An aircraft operating with low-thrust engines has little choice in the range of fuel-efficient operation, as shown in Figure 4-3. Maximum rate of climb is at some speed between the two points crossing the horizontal axis. It is never advantageous to operate an aircraft in the left half of the curve because more altitude and downrange speed can be gained for the same unit of time by operating in the center. Higher thrust engines can operate within the greater range of the outer curve. As altitude increases, the thrust output of the engines decreases, and rate of climb becomes slower and slower. At the altitude where level flight at full power can just be maintained, the service ceiling of the aircraft has been reached.

Thus, higher thrust engines can climb at a faster airspeed and a faster rate of climb than low-thrust engines on the same aircraft type, as shown in Figure 4-3. A higher thrust aircraft reaches the most efficient cruise altitude faster and stays there longer. Because of this, fuel mileage will be better with a higher thrust engine, other things being equal. Of course, higher thrust engines could be more costly, heavier, and have more drag because of their size. These factors must be considered by an aircraft designer when selecting an engine for a particular airframe.

4.5.2 Weight

Increasing the weight of an aircraft has the same effect as decreasing its engine thrust. Rate of climb suffers, and the aircraft requires more time and distance to reach cruise altitude. The heavier aircraft flies more efficiently at a faster airspeed in all phases of flight, and its most fuel-efficient altitude is lower than for a lighter aircraft. It also follows a shallower angle for the most fuel-efficient descent.

Table 4-3 shows sensitivities of climb profiles to weight. The lower weight figure for each aircraft type represents an empty aircraft; the higher figure represents a full or nearly full one. The variance in climb speeds among the aircraft types presented seems to depend more on aircraft loading than anything else. It is probable that an accurate regression model could be developed to relate aircraft climb speed to the thrust/weight ratio of the aircraft, or more simply, to the revenue load factor.

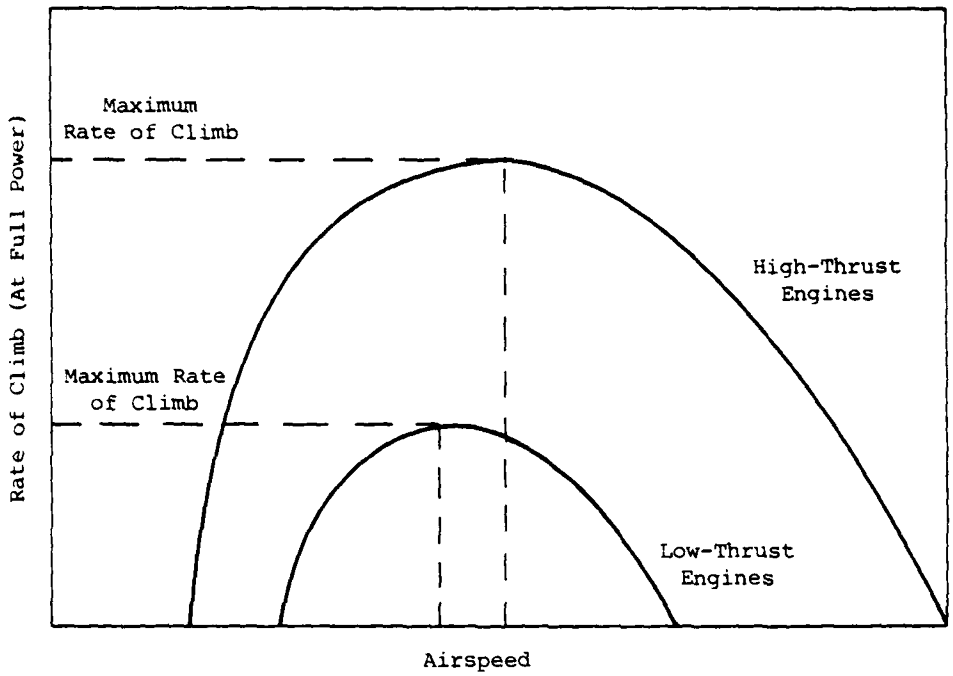


Figure 4-3. EFFECT OF THRUST OUTPUT ON CLIMB/CRUISE LATITUDE

In a cruise-climb profile (in which the aircraft climbs 10 to 15 feet per minute to remain at its optimal altitude) there is little variation in cruise mach number, regardless of weight or altitude, although true airspeed may change as a result of the changing temperature. However, when an aircraft is cruising at a constant altitude, its *optimal mach number* decreases as fuel is burned off. For example, a DC-10 cruising at 33,000 feet with a gross weight of 400,000 pounds has a long-range cruise speed of 0.821 mach (M). By the time 30,000 pounds of fuel have been burned (about 1,000 nautical miles down range) the long-range cruise speed has decreased to 0.814 M. If the pilot then executes a step climb to 37,000 feet and levels there, his initial cruise speed should increase to 0.826 M as a result of the climb. As additional fuel is burned at the new altitude, the optimal mach number again decreases slowly until the next step climb is executed.

4.5.3 Wind

Wind affects the optimal airspeed. In general, airplanes should speed up in the presence of a headwind and slow down for a tailwind for the greatest fuel efficiency. However, the effects are different for each phase of flight. This section discusses wind effects on climb profiles. The cruise segment of flight is discussed in Section 4.6 and the descent segment in Section 5.2.

Table 4-3. AIRCRAFT CLIMB PERFORMANCE (FUEL COST - 12.6¢ PER POUND)

Aircraft Type	Engines	Takeoff Weight (Pounds)	IAS Climb at 15,000 Feet	Climb Rate (Feet Per Minute)	Pitch (°)	Maximum Climb Fuel Consumption (Pounds per Hour at 15,000 Feet)
DC-9-10	JT8D-5	62,000 (empty)	343*	3,400	4.5	12,600
		82,000 (full)	360	2,100	2.7	
727	JT8D-15	108,000 (empty)	308	2,400	3.5	16,500
		160,000 (full)	317	1,400	2.1	
L-1011	RB211-22B	250,000 (empty)	319	2,700	4.0	31,000
		350,000 (full)	332	1,900	2.6	
747	JT9D-3	400,000 (empty)	314	2,000	3.0	42,000
		550,000 (full)	325	1,300	1.9	

*The best climb speed calculated from the analysis of drag polars exceeds the maximum operating speed of 340 KIAS for this aircraft type.

Figure 4-4 shows the sensitivity of trip cost to indicated climb speed for a 40-knot headwind, no wind, and a 40-knot tailwind. The best no-wind climb speed is the low point of the middle curve, or 317 KIAS. The low points of the upper curve, representing headwind, is 324 knots; for tailwind, the best speed appears to be 315 knots. Each of the curves shows a large region over which there is very little variation in cost; consequently, it is somewhat difficult to precisely select the low point of the curve. Nevertheless, the variation in indicated airspeed resulting from an 80-knot variation in wind (40-knot headwind to 40-knot tailwind) is only 9 knots (324 - 315) or about 0.1 knot of speed per knot of wind. Furthermore, if this 9-knot correction is not made, the cost penalty is very small since the curves are so flat near the minimum points. Because of measurement errors at such low levels of speed change and the small number of data points on which the minimum was determined, the measured factor of 0.1 knot per knot of wind is not considered significant. Given the low sensitivity of overall cost to climb speed and the low compensation factor, accounting for wind in climb does not warrant major fine-tuning from the crew.

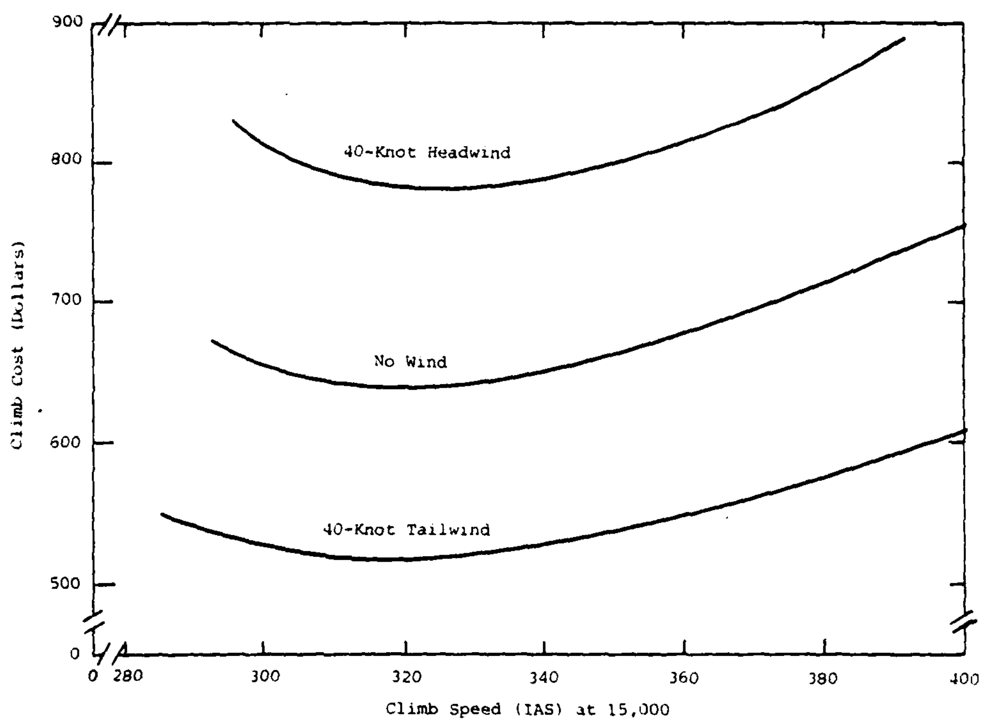


Figure 4-4. CLIMB COST VERSUS CLIMB SPEED FOR VARIOUS WIND CONDITIONS (727-200, 300 NAUTICAL MILES)

4.6 CRUISE PERFORMANCE

All data presented in this section were extracted from cruise tables for the 727-200, DC-9-50, and DC-10-10. Effects of wind and temperature are not considered.

4.6.1 Unrestricted Cruise Profile

In the absence of air traffic control constraints, fuel-optimal or cost-optimal cruise altitude depends on aircraft gross weight. The lower the aircraft weight, the higher the optimal altitude. For a DC-10, the optimal altitude varies from about 33,000 feet for a fully loaded aircraft to about 41,000 feet for a nearly empty aircraft. The engines of some of the older aircraft, such as the 727-100, are not powerful enough to reach their optimal altitude, particularly with a heavy load. Under these circumstances they would simply climb to the highest possible flight level that would permit level cruise flight with adequate buffet margins.

In the unconstrained cruise profile, the gross weight of the aircraft will be decreasing as fuel weight is burned off; therefore, the optimal altitude will be slowly increasing. Thus, it will be necessary for the pilot to add a little extra thrust to maintain a rate of climb of 10 to 20 feet per minute to keep the aircraft at its optimal altitude. Such a profile cannot be flown in an ATC environment, but it is important to evaluate the unconstrained case as a bestcase scenario to which all other constrained scenarios can be compared.

For a given altitude, the optimal cruise mach decreases as weight decreases. However, for a given weight, the optimal mach number increases as altitude increases. These two effects essentially cancel each other, so that the optimal mach number in an unconstrained cruise-climb profile is approximately constant, independent of altitude and weight, and depending only on the aircraft type. Table 4-1 showed the long-range cruise speeds for various aircraft types. Optimum cruise speeds for the heavier aircraft tend to be faster. Subsequent analysis in this section will assume long range cruise speed to be the minimum-cost speed.

Aircraft operating at high altitudes are limited by the stall and mach buffet margins, as shown in Figure 4-5. If airspeed becomes too low, a stall condition results in aircraft buffeting and a dangerous loss of control. If speed gets too high, a similar buffeting results from portions of the airframe attaining supersonic airspeed, placing unbalanced drag loads on the airframe. As altitude increases, the acceptable range of operating speeds becomes smaller. The pilot must be careful to operate the aircraft with enough margin of safety so that gusts or turbulence will not cause the aircraft to stall or suffer mach buffeting.

4.6.2 ATC Restrictions in Cruise

ATC imposes three major constraints on flight profiles in cruise that affect fuel performance: (1) route restrictions, (2) altitude restrictions, and (3) speed restrictions.

In domestic airspace, IFR traffic usually flies on established airways. Departing traffic may find it necessary to divert substantially off a direct course to intercept such an airway. Obviously, trip distance could be reduced by flying direct (great circle) routes, but ATC procedures are not set up for this, and direct clearances are granted only when controller workload permits. The airlines' flight planning activities are tailored to the airways structure. Consequently, airlines seldom request a direct clearance,

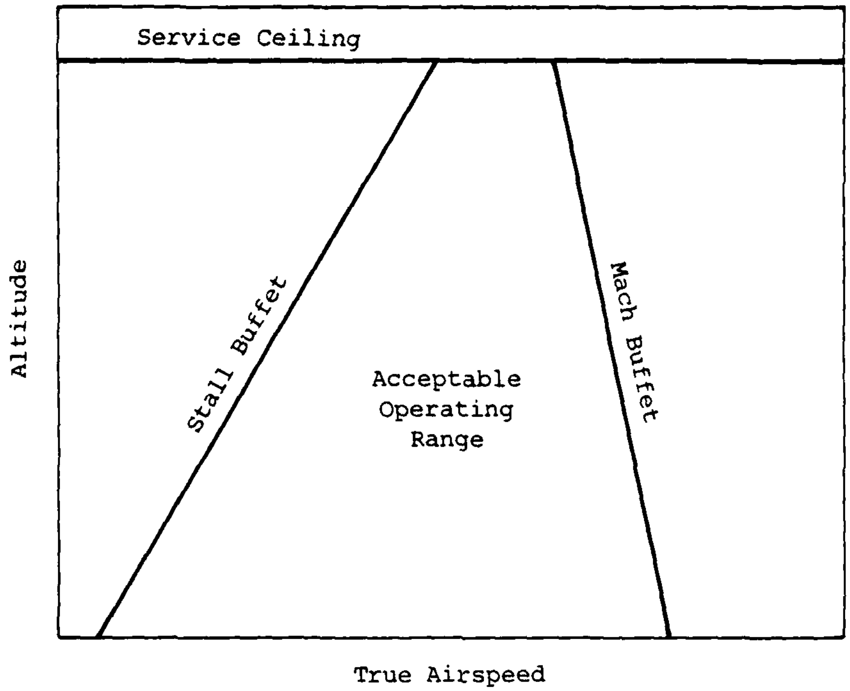


Figure 4-5. BUFFET MARGINS

even when controller workload would permit it. Although area navigation (RNAV) equipment is now commercially available to permit navigation along any direct course, limited ATC accommodation of this capability has limited the air carriers that have installed the equipment in their aircraft. As a percent of total stage length, short-haul carriers, for whom the established airways may not be ideal, would realize maximum savings from RNAV. Long-haul carriers have much greater flexibility in their choice of routes, even when restricted to the standard jet airways.

For long-haul cruise operation, aircraft are normally restricted to flight levels 310, 350, and 390 westbound, and 330, 370, and 410 eastbound. This is significant because the assigned flight level may be considerably off the unconstrained optimal altitude for a given weight. Performance limits of aircraft may prevent it from climbing to the next flight level, say 370, until the optimal altitude is up to about FL 360. By that time, the aircraft cruising at FL 330 will be paying a measurable fuel penalty. Some airlines try to minimize this problem by requesting a 2,000-foot step-climb to a non-standard altitude (e.g., FL 370 westbound) whenever possible.

The preceding analysis assumes that the aircraft can get the altitude it wants, but this is not always the case. In some sections of the country, particularly the Northeast, certain airspace is reserved for traffic flying a particular direction (as, for instance, east-west traffic), thereby closing that airspace to traffic flying other directions, even when the space is clear of traffic. These altitude crossing restrictions are logistically convenient because they allow sector controllers to manage the traffic in their sectors with minimal coordination with other controllers in adjacent sectors. Reducing coordination calls cuts controller workload and makes higher controller productivity possible. However, these airspace restrictions often force aircraft into a fuel-inefficient low-altitude cruise until they pass by the reserved airspace.

Speed constraints are seldom imposed in domestic en-route airspace. Carriers file their flight plans for a particular speed, and ATC would be unconcerned if they deviate slightly. Unlike the unconstrained cruise-climb case, step-climb profiles require minor changes in speed. Mach number will be highest upon reaching a new flight level and decrease slowly until time for the next step climb or the top-of-descent point is reached. These speed changes are small and very slow and would not be significant to a controller within a single en-route sector. On transatlantic flights, however, aircraft are not usually permitted to change either altitude or speed while over the ocean. These restrictions impose an increasing fuel penalty as the flight progresses. These penalties will be quantified in Section 4.6.4.

4.6.3 Effect of Routing Constraints in Cruise

Figure 4-6 shows a plot of typical percentage differences in trip distances between direct (great circle) routes and conventional IFR routes along established airways.* In percentage terms, savings are greater for shorter stage lengths, although the absolute number of miles saved increases with stage length. The percentage measure is more meaningful when considering the impact on costs per seat mile or passenger mile. The regression line should be considered only a rough indicator of potential savings. Even though most points lie near the regression line, the savings achievable for a particular route could deviate significantly from the trend, depending on the takeoff and landing runways being used, location of nearby VORs, and location of restricted airspace in the route of flight.

Of course, there are operational problems with routine direct clearances. At most terminal control areas, certain airspace is blocked off for departures and other for arrivals. It is possible for a departing aircraft to fly through arrival sectors, but the presence of an aircraft going counter to the flow in those sectors creates a major burden for the controller and possibly a safety hazard as well. As a result, unless traffic is very light, a direct clearance for a departing aircraft through arrival airspace is very unlikely. Even if direct routings were always available, the airlines would not necessarily use them. If taking advantage of favorable winds aloft would require adding 50 miles to the route of flight on a transcontinental trip, it might be in the airlines' interest to do so. The airlines do not necessarily choose the shortest airway route for long trips. If RNAV were available, an airline might choose to fly direct routes to three or four intermediate waypoints selected to take maximum advantage of prevailing winds or to avoid severe weather.

*The majority of the data points in Figure 4-6 were taken from Reference 37, but the three short-haul segments were calculated independently.

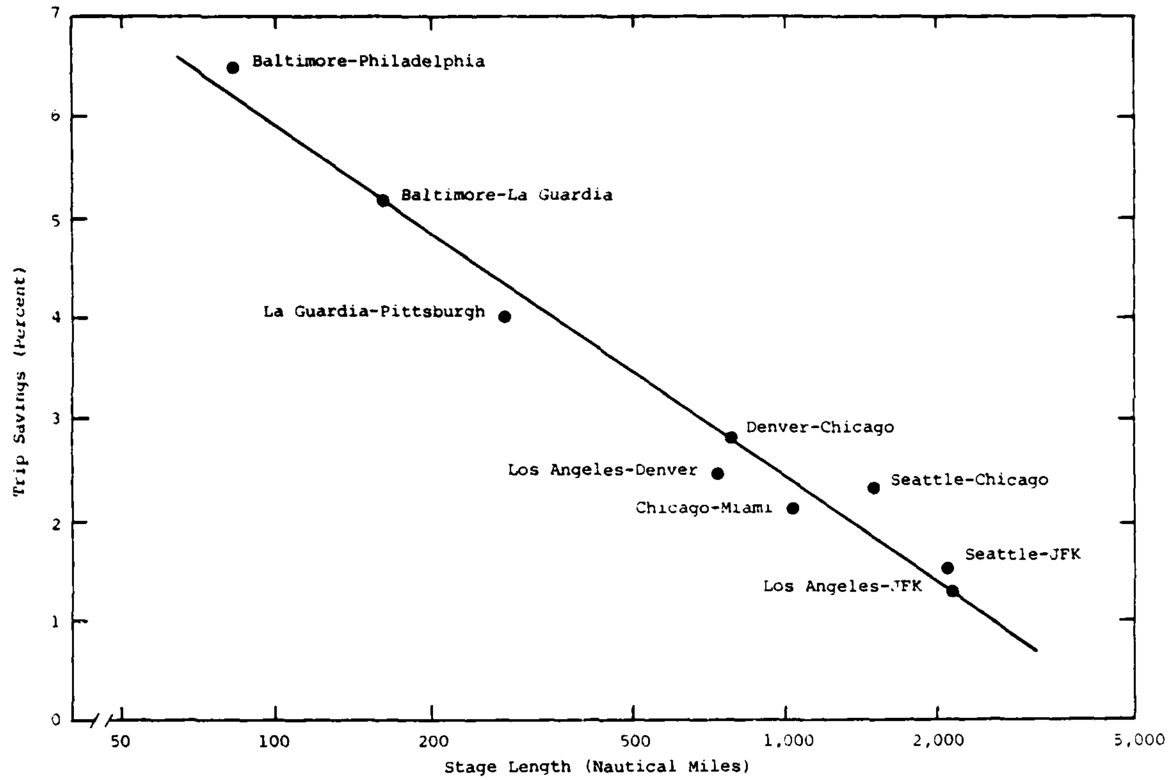


Figure 4-6. POTENTIAL SAVINGS FROM DIRECT RNAV ROUTES

There would be little or no payoff from optimizing routes to allow for winds of typical weather systems on short-haul flights. For trips of 300 nm or less, the direct route is almost always the best route. While routine direct clearances would benefit all RNAV-equipped aircraft, the biggest cost payoff would be for short haul and commuter flights.

4.6.4 Effect of Altitude and Speed Restrictions

For the purpose of calculating the effect of altitude and speed restrictions, a cruise segment of about 4,000 nautical miles on a DC-10 will be considered. The aircraft will be assumed to weigh 400,000 pounds at the beginning of cruise and 280,000 pounds at the end. On the basis of performance data, specific range and average speed for various flight scenarios can be calculated and time and fuel burn for a 4,000-nautical-mile cruise segment normalized.

The scenarios to be considered represent different flight trajectories. The baseline is the optimal cruise-climb trajectory. This scenario is the best combination of speed and altitude to minimize flight cost, but practically, it cannot be flown in an ATC environment because of the large volume of airspace that would be taken by such a profile. Two scenarios were developed for step climb flights, one eastbound (FL 330, 370, 410) and one westbound (FL 310, 350, 390). An additional scenario can be inferred by assuming 2,000-foot step climbs. Three additional scenarios characterize the trans-oceanic environment where the aircraft must hold a fixed altitude and mach number. Cases for 0.826 M (long range cruise) and 0.810 M (maximum range cruise) were analyzed. One additional scenario was run in which the aircraft was permitted to slow down while maintaining a constant altitude in order to measure the effect of that restriction.

Specific range was calculated at each point of the flight in accordance with tables in the DC-10 performance manual.

Results are plotted in Figure 4-7. All statistics are shown relative to the unconstrained cruise-climb trajectory (solid black line in the figure). Fuel performance in the unconstrained flight increases from 28.7 nmi/1,000 pounds at 400,000 pounds gross weight to 40.8 nmi/1,000 pounds at 280,000 pounds gross weight (not apparent in the figure). Therefore, on a percentage basis,the loss of 1 nmi/1,000 pounds of fuel represents 3.5 percent at the left end of the graph and 2.5 percent at the right end. The area under the curves (or between curves) represents a loss in specific range. Either cruise climb or step climb requires additional thrust energy above what is needed for level cruise in order to increase the potential energy (altitude) of the aircraft. In a cruise climb there is a small but continuous level of additional thrust. A step climb requires a greater level of thrust but only for a short time. It is assumed that the additional energy necessary to achieve the new altitude is the same in either case. This assumption allows the problem to be analyzed as a steady-state situation without consideration of gross power changes required during the short climb segments.

The step-climb cases show that loss of specific range becomes measurable when the optimum altitude is only about 1,000 feet above the cruising altitude, and gradually increases until the step climb is made. For the eastbound case, step climbs are executed at 370,000 pounds and 305,000 pounds gross weight; for westbound at 340,000 pounds only. After making the step, measured fuel performance returns to its optimum value. While the loss in specific range could be cut if the aircraft began its step climb earlier, it does not have the thrust power available to do so. The step climb strains the performance limits of the aircraft to the point that after the aircraft has leveled off at the new altitude it will initially be cruising at maximum cruise thrust. This leaves little margin for miscalculation since the airplane is operating close to its performance limits. Pilots must be sure that adequate buffet margins can be maintained at the higher altitude; unforecast turbulence can make this more of a problem. Sometimes the temperature at the new altitude will be warmer than expected and the aircraft will not be able to maintain altitude, and therefore must come back down. As a practical matter, therefore, pilots try to assure some margin for error when they decide to step climb.

For shorter cruise segments, say 1,500 miles, the fuel penalty depends to some extent on how close the optimal altitude is to the assigned altitude. For example, an eastbound aircraft that begins its cruise with a weight of 365,000 pounds can climb immediately to 37,000 feet, cruise there for about

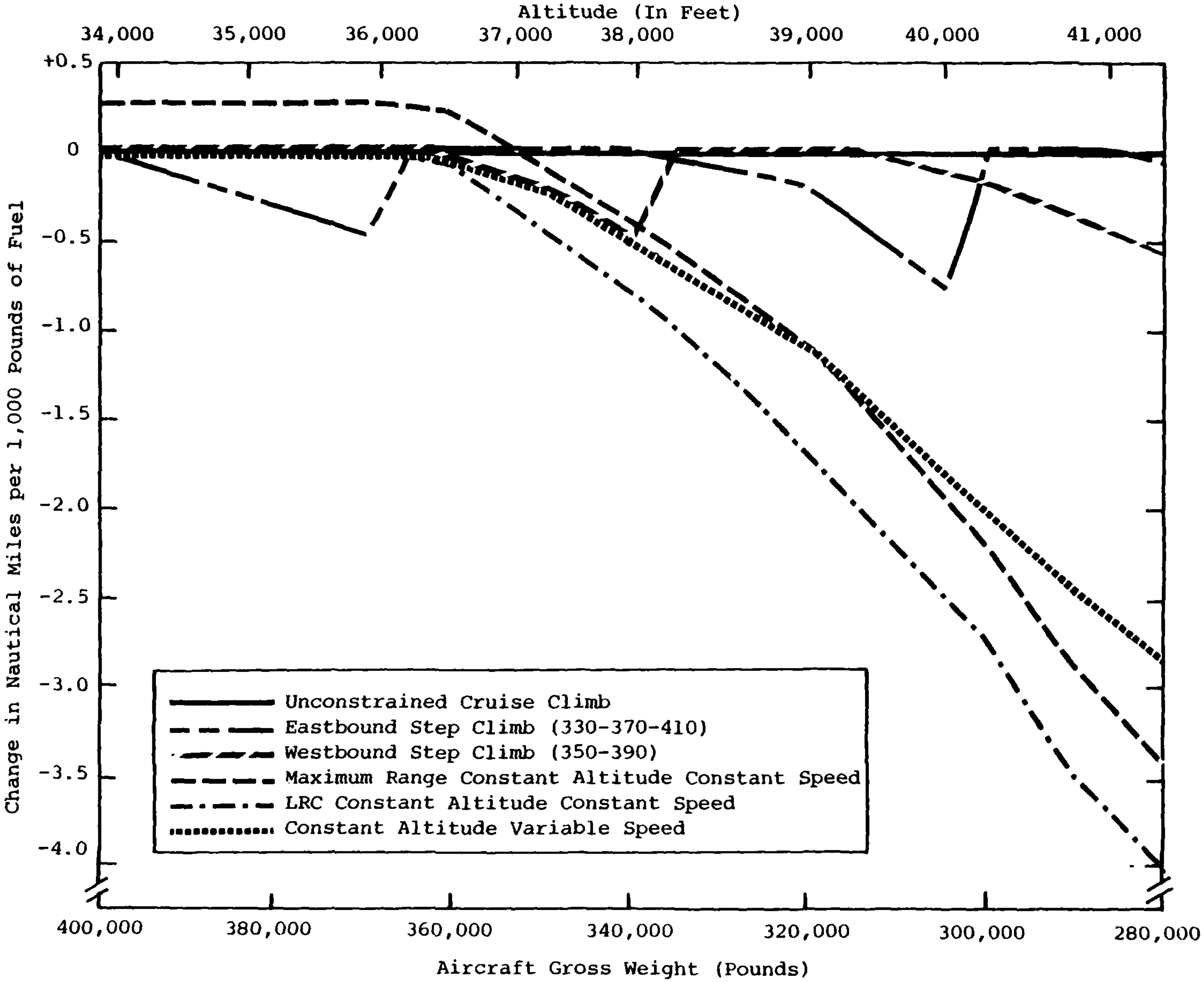


Figure 4-7. CHANGE IN SPECIFIC FUEL CONSUMPTION FOR SIX FLIGHT SCENARIOS

two hours (using 30,000 pounds of fuel) and pay almost no penalty in fuel mileage (calculated at 0.01 percent). However, the same aircraft westbound will have to cruise at 35,000 feet and will incur a fuel penalty of 0.58 percent. If 2,000-foot step climbs are permitted, losses in specific ranges are reduced to nearly zero regardless of trip parameters. This is represented by whichever of the step climb curves is closest to optimum. Only at altitudes greater than 39,000 feet is any difference measurable at all. Decreasing vertical separation at these altitudes to 1,000 feet would have an equivalent effect, since 2,000 foot step climbs would become routine.

Much greater penalties are paid in the constant-altitude cruise cases. For a constant speed of 0.826 M, the instantaneous fuel penalty is as high as 4 nm per 1,000 pounds of fuel, or 9.8 percent. The overall penalty is much less because the gap in fuel performance between the unconstrained cruise-climb case and the constant altitude case becomes greater and greater as the flight continues. However, some time is saved because of the higher true airspeed (the speed of sound decreases with increasing altitude). By cruising at 0.810 instead of 0.826 M, the pilot is choosing the fuel-optimal speed (maximum range cruise). This speed initially produces better specific range than any of the long-range cruise profiles, but at a substantial expense in time. Specific range is increased by 49 miles over the 0.826 M case (1.23 percent) with a corresponding time penalty of 9.9 minutes (1.95 percent).

Fuel performance can be improved if the pilot is permitted to slow down in the course of the cruise, reaching 0.799 M at the end. This increases the specific range by 46 miles (1.2 percent), but also increases time by 8.2 minutes (1.6 percent).

Table 4-4. LONG-HAUL PROFILES

Scenario	Fuel Burned (Pounds)	Difference From Baseline	Percent Change	Time (Minutes)	Difference From Baseline	Percent Change	Cost Difference	Percent Change
1. Baseline Cruise Climb	117,740	---	---	503.6	---	---	---	---
2. Step Climb - East	118,220	480	0.4	505.6	2.0	0.4	$116.40	0.4
3. Step Climb - West	118,100	360	0.3	506.1	2.5	0.5	115.55	0.4
4. 35,000 Feet at 0.86 M	120,160	2,420	2.1	511.9	8.3	1.6	542.85	1.9
5. 35,000 Feet at 0.826 M	121,490	3,750	3.2	502.0	-1.6	-0.3	443.50	1.5
6. 35,000 Feet at Variable	120,240	2,500	2.1	510.2	6.6	1.3	506.50	1.7
7. 2,000-Foot Step Climb	117,790	50	0.0	504.9	1.3	0.3	42.25	0.1
Total Flight Cost of Baseline = $29,155.20								

Basis of Calculations: Segment Length - 4,000 nautical miles
Initial Weight - 400,000 pounds
Time Cost - $1,650 per hour
Fuel Cost - $00.126 per pound

Summary results for all cases are shown in Table 4-4. The necessity of step climbing in flight (cases 2 and 3) adds about 0.4 percent to trip costs over the costs of optimal cruise climb. This is true for both the eastbound and westbound cases, although a scenario could be developed where direction would make a difference. If 2,000-foot step climbs were to become routine, either by mixing eastbound and westbound traffic or by going to 1,000-foot vertical separation, the overall penalty would be reduced to 0.1 percent (case 7). These figures are dwarfed by the costs of maintaining a constant altitude and constant speed cruise (cases 4 and 5). Carriers will burn 3.2 percent more fuel under these circumstances than in the unconstrained case. Because of time/fuel cost trade-offs, the aircraft will get back 0.3 percent of flight-time costs, increasing overall costs by 1.5 percent of trip costs (case 5). The ability to change cruising speed allows fuel savings but costs time and therefore would not significantly affect carrier behavior (case 6).

4.6.5 Wind Effects on Cruise Profiles

To compensate for wind, pilots should increase airspeed for a headwind and decrease it for a tailwind, as outlined in Section 2.2. However, the magnitude of the compensation depends on the altitude and mach number of the no-wind cruise profile.

Figure 4-8 shows graphs of range versus airspeed for five different wind conditions. The data are for a DC-10 with a gross weight of 340,000 pounds cruising at 15,000 feet. The curves show that true airspeed should be increased about 0.4 knot for each knot of headwind and decreased about 0.25 knot per knot of tailwind. These factors apply to both long range and max range cruise. The shape of the performance curves shows that compensating for tailwinds always requires adjustment less than or comparable to compensation for headwinds in all phases of flight. Under most circumstances, the DC-10 pilot would not voluntarily cruise at 15,000 feet, so this analysis represents the situation in which the aircraft is held there by ATC or is flying a short segment.

At a high altitude and high mach cruise, the situation is different, as shown in Figure 4-9. At 37,000 feet and max range cruise, with a no-wind true airspeed of 461 knots, the adjustment for 100 knots of tailwind is to slow to 457 knots, or 0.04 knot per knot of wind. For headwinds, the adjustment is to 466 knots, or 0.05 knot per knot of wind. For long range cruise, the adjustment is even less. Under these conditions, the adjustment is so small and the payoffs so small that most airlines do not bother to make the adjustments.

Analysis of intermediate altitudes shows that the low-altitude model can safely be used for altitudes below 25,000 feet and speeds below 0.7 M. For altitudes above 31,000 feet and speeds above 0.75 M, the high altitude model is applicable. In between is a gray area that could go either way depending on gross weight or temperature.

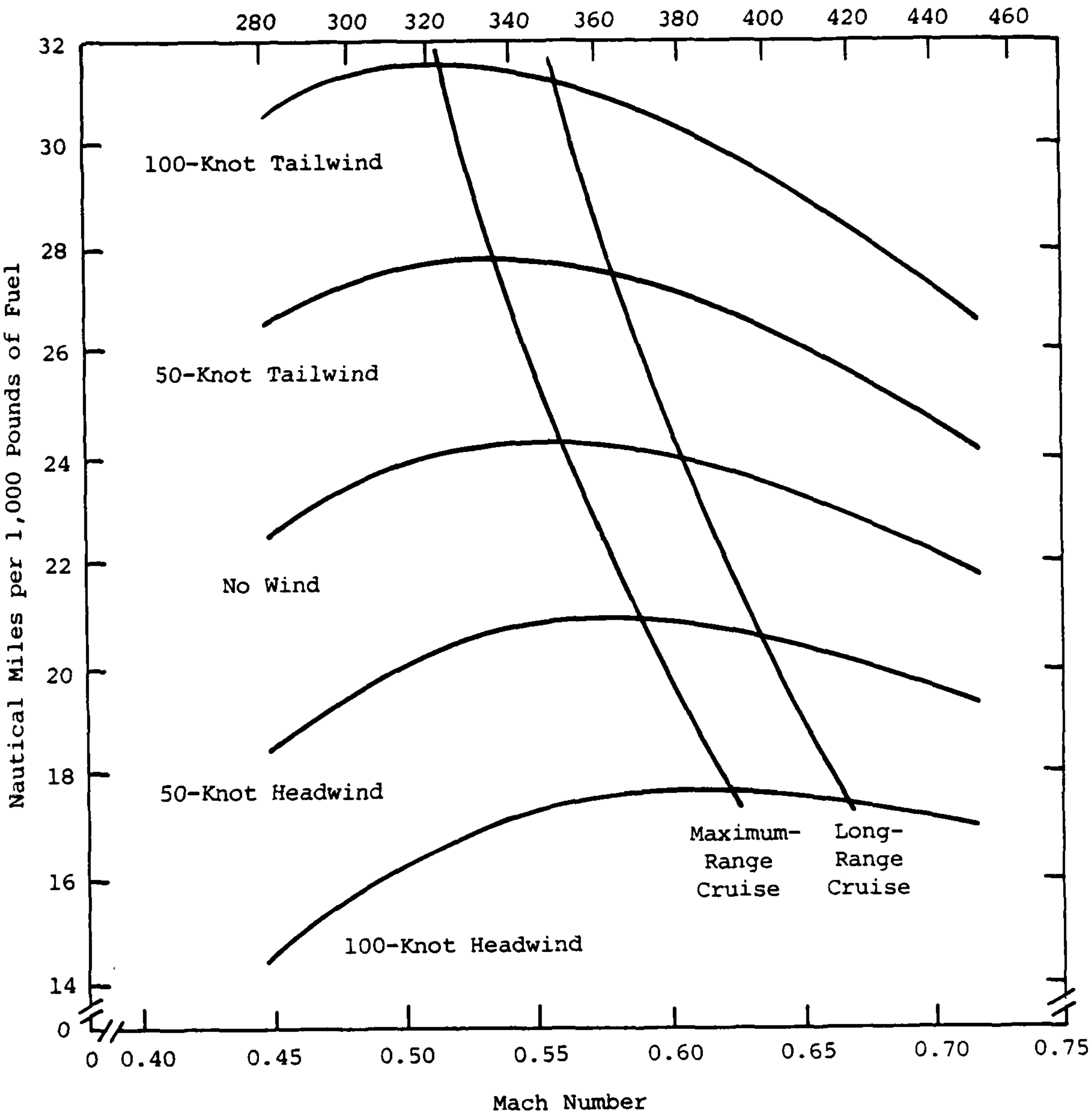


Figure 4-8. WIND EFFECTS ON FUEL MILEAGE -- LOW ALTITUDE CRUISE (DC-10, 340,000 POUNDS, CRUISING AT 15,000 FEET)

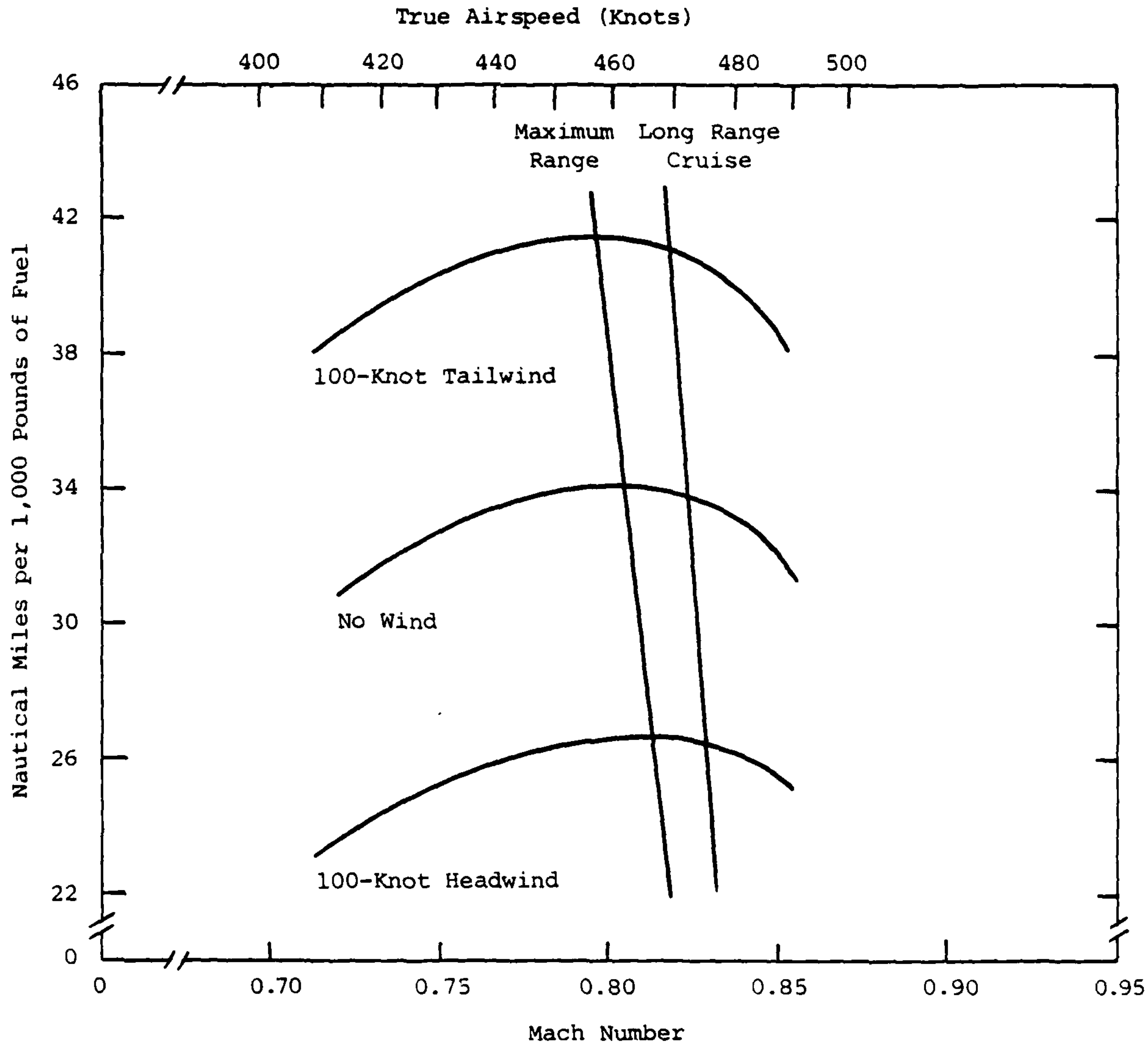


Figure 4-9. WIND EFFECTS ON FUEL MILEAGE: HIGH ALTITUDE CRUISE (DC-10, 340,000 POUNDS, CRUISING AT 37,000 FEET)

CHAPTER FIVE

FLIGHT PROFILE MANAGEMENT IN THE TERMINAL ENVIRONMENT

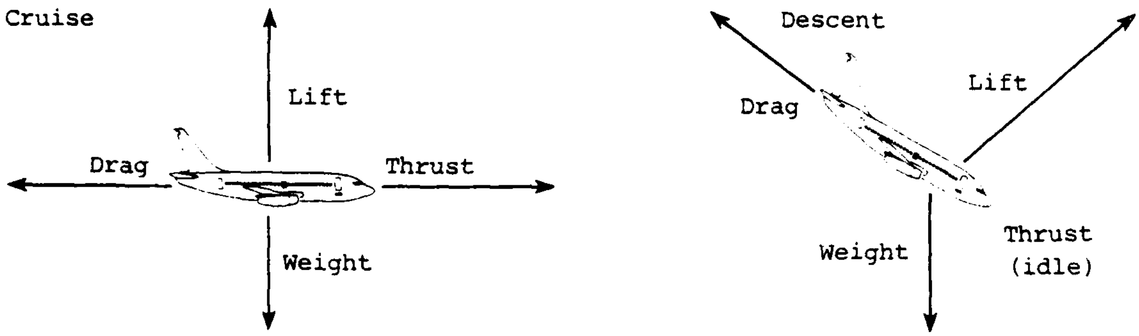
5.1 INTRODUCTION

Descent into a terminal area is the phase of flight that typically requires the least fuel but causes the most problems for ATC. At many airports, limited runway capacity limits traffic growth and causes delays during peak periods. It is in descent, however, where flight management computers offer a potential for cost savings through descent speed management, selection of proper top-of-descent point, and optimal absorption of ATC delays. This chapter discusses flight management issues from cruise altitude to final approach. It examines the unconstrained minimum cost profiles and the costs of deviation from those profiles. Also discussed are some simple delay management cases and the sequencing problems resulting from aircraft descending at different speeds.

5.2 COMMON DESCENT CHARACTERISTICS

Descent involves the process of converting the potential energy of an aircraft at cruise altitude and speed into downrange distance through progressive decreases in altitude. No additional thrust energy is necessary to effect a descent because the aircraft is recouping all the extra energy it used to overcome gravity during climb (see Figure 5-1). Thus, descent profiles are usually executed at idle thrust. The pilot can control the airspeed by adjusting the pitch angle up or down. A steep angle will result in a rapid conversion of potential to kinetic energy and consequently a fast descent. A shallower angle will effect a slower descent, and greater downrange distance can be obtained. A fast descent must be begun later in the flight because it traverses less distance over the ground (see Figure 5-2). If this is not done, the aircraft will be forced to execute a costly low-altitude cruise to make up the additional distance.

Idle thrust burns fuel at a rate of approximately 10 percent of maximum climb or cruise power. The idle fuel burn increases with increasing mach number and increasing air density (decreasing altitude) due to the increased rate of air flow through the engine turbines. Since the engines are operating at low power, fuel costs are a small fraction of what they are in cruise, while the time-related costs accumulate at the same rate. Thus, even



Thrust + Drag = 0
Lift + Weight = 0

Lift + Drag + Weight = 0

Figure 5-1. FORCE VECTORS IN STEADY STATE CRUISE AND DESCENT

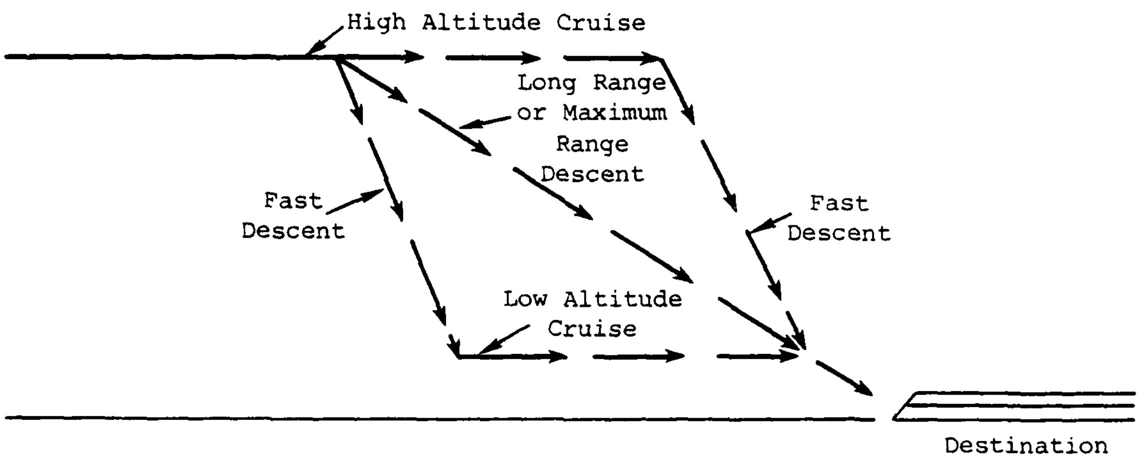


Figure 5-2. DESCENT OPTIONS

at today's fuel prices, descent costs are dominated by time. Airlines are willing to descend at speeds well in excess of the fuel optimal speeds because the cost of the extra fuel burned is more than offset by time savings of a faster descent.

An analysis of drag polars of an aircraft in descent shows that an optimal descent profile is maintained by holding a constant indicated air speed (IAS). For a constant IAS descent, the true airspeed is continuously falling, but the descent angle is constant. For the above reasons, descent profiles are usually discussed in terms of indicated airspeed, rather than true airspeed (useful for calculating ground track time) or mach number (useful in analyzing many measures of performance).

In an ATC environment, descent to a terminal area usually begins in Air Route Traffic Control Center (ARTCC) airspace, in which the lower density of traffic seldom imposes a restriction on a pilot trying to descend. As the aircraft nears the airport, however, increasing traffic may force controllers to vector the aircraft off course or hold at an intermediate altitude, either of which can reduce or eliminate any savings resulting from careful flight management. This chapter will address the issue of descent flight profiles both with and without ATC constraints.

5.3 MINIMUM-COST DESCENT PROFILES WITHOUT ATC CONSTRAINTS

5.3.1 Method

The fuel burn model was used to generate flight profiles for various aircraft types, descent speeds, and operating weights. In order to ensure that results from alternative profiles would be directly comparable, it was necessary to begin and end each profile at the same set of positions, altitudes, and speeds. Accordingly, each profile began at an altitude of 30,000* feet at cruise mach speed and ended at an altitude of 10,000 feet at 250 knots IAS, covering a distance of 150 nautical miles. At the end of descent (at 10,000 feet and 250 knots) aircraft are presumably sequenced for approach and landing. By beginning and ending each profile at the same altitude and speed, the fuel burned and flight time spent can be directly compared.

The analyses in this section are based primarily on data for the 727-200 aircraft. This is the most common aircraft in the current fleet, accounting for about one third of all air carrier operations in 1979. Furthermore, its size is between smaller jets like the DC-9 and 737 and the wide bodies such as the 747 and DC-10. Although its technology will be obsolete by the end of the 1980s, it will continue to be the most common model in the fleet for several more years. Performance data for the aircraft that will replace it do not exist at this time. It is assumed that conclusions presented in this section based on the current fleet will be applicable to the fleet of the late 1980s.

5.3.2 Time, Fuel Trade-offs

Figure 5-3 shows time-fuel trade-off curves for the 727-200 for four possible aircraft weights. A 108,000-pound aircraft represents an empty airplane. The zero fuel weight of the aircraft is 102,000 pounds; adding required fuel reserves and crew weight yields the 108,000 pounds figure. This is the lightest weight this aircraft type can be expected to have in landing. A 160,000-pound airplane is full. It contains about 160 passengers weighing 200 pounds each (including all baggage) and a moderate amount

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*While 30,000 feet is not a presently authorized cruise altitude, it was used in these analyses for computational convenience.

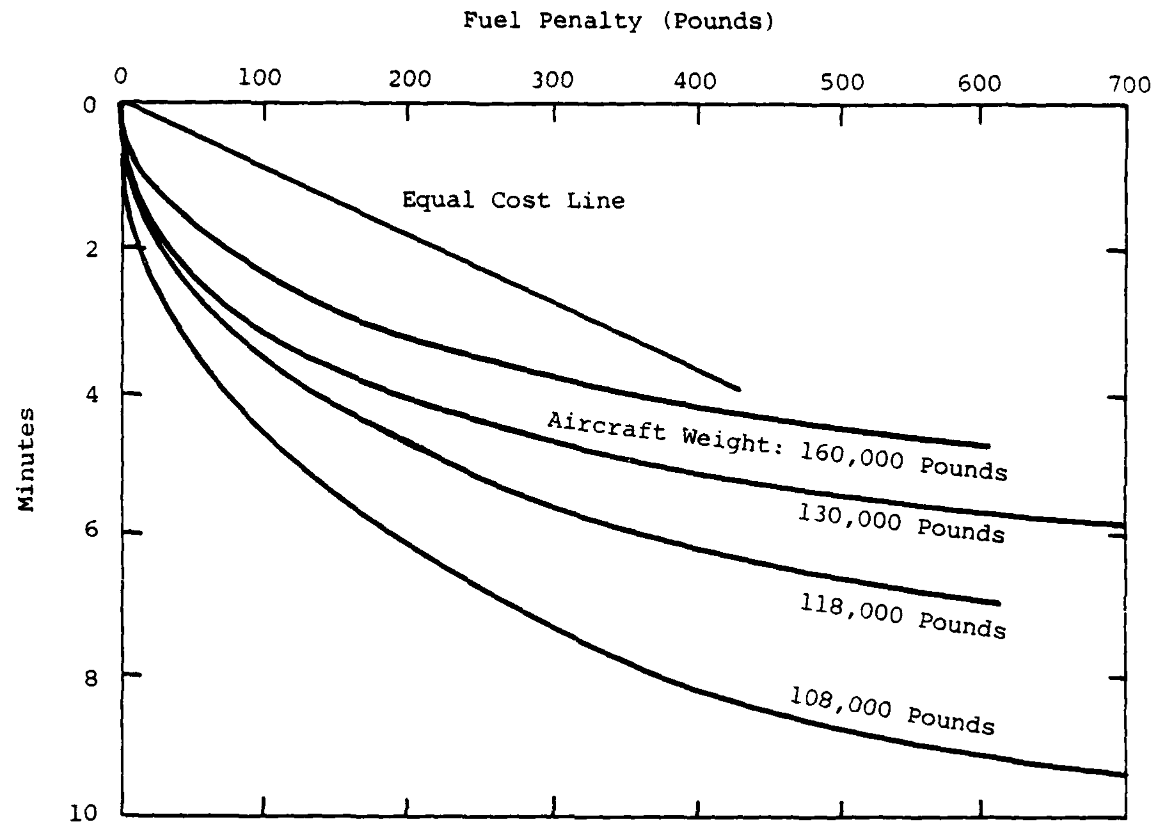

Figure 5-3. TIME-FUEL TRADE-OFFS FOR 727-200 DESCENT

of additional cargo and fuel. The origin of the graph is the fuel-optimal profile and is the slowest possible profile that can be flown. The airplane could go even slower, but then it would use both more fuel and more time. Any faster profile saves time at the expense of fuel consumption.

Depending on unit time and fuel costs, a line can be drawn through the origin indicating an equivalent trade-off of time and fuel expenses. At current costs of $0.126 per pound of fuel and $13.75 per minute, the line shown in the figure results. All points on this line represent a balanced trade-off between time and fuel costs. For example, 300 pounds is equivalent to 2.75 minutes. Since the value of time saved equals the value of additional fuel burned for all points on the line, the line represents a zero-cost trade-off between time and fuel. Any line parallel to this line will represent a constant, but nonzero cost trade-off, since the slope is the same but the intercept different. A parallel line drawn below another indicates a lower cost and therefore a greater savings. Thus, the proper operating point for a particular weight is the point where an equal cost line is tangent to the curve. For lower fuel prices, such as those existing in the early 1970s, the equal-cost lines will be flatter, intersecting further down the curve. For higher prices, the cost lines are steeper. In the fuel-optimal case, time has no value; the cost lines are vertical; and the aircraft will operate at the origin of the curve.

5.3.3 Effects of Fuel Prices

As a general rule, the best descent speed will increase with decreasing fuel prices and increasing weight. Figure 5-4 shows the sensitivity of minimum-cost descent speed to aircraft loading (weight) and fuel price. A fuel price of 85¢ per gallon equates to a 60 percent share of direct operating costs attributable to fuel. This corresponds with the current situation. Depending on weight, the cost-optimum descent speed varies from 270 to 285 KIAS. As fuel costs approach 100 percent of direct operating costs, sensitivity to weight is maximum. The fuel-optimal speed is that which maximizes the ratio of lift to drag. A drag polar analysis shows that this speed is proportional to the square root of the aircraft weight. Figure 5-4 shows that the carriers' current efforts to slow their descents from the high-speed levels of the early 1970s is a sound and cost-effective policy.

The requirement to slow to 250 KIAS below 10,000 feet means that unless the minimum-cost speed is below 250, the aircraft must execute its descent to 10,000 feet then level and bleed off speed to 250 KIAS before it can continue the descent. In a clean configuration it takes about 1.6 minutes to slow from 350 to 250 KIAS in level flight at idle power. If fuel is not a major cost factor, the time may be so relatively valuable that it is not cost-effective to wait. At low fuel prices, therefore, it can actually be cost-effective to use the speed brakes to reduce speed to 250 KIAS, and use them again in the final descent to reduce the time spent in descent. At current fuel prices, however, descent speeds are slower, and the use of speed brakes in any phase of descent is to be avoided.

5.3.4 Cost Sensitivity

Figure 5-5 shows the sensitivity of cost to descent speed, assuming current fuel prices. The figure can be used for the calculation of the cost penalty for flying at an off-optimal speed. The sensitivities to speed appear to be quite small. At the low gross weight of 108,000 pounds, the cost-optimal descent speed is 270 KIAS; however, any speed between 240 and 315 knots will be less than 1 percent (about $5) more costly. For a full airplane (160,000 pounds), the sensitivity is greater, but a range of speeds between 256 and 307 KIAS can still be flown to maintain 99 percent or better cost-effectiveness. Thus, for the 727-200, descent cost is relatively insensitive to descent speed.

5.3.5 Effect of Wind

Many air carriers use wind forecasts for the purpose of route planning and calculating point of descent only, then fly their routes without paying further attention to wind. However, proper flight management requires that the profile be continuously updated according to the wind. A headwind should be handled by increasing airspeed, thereby staying longer at altitude

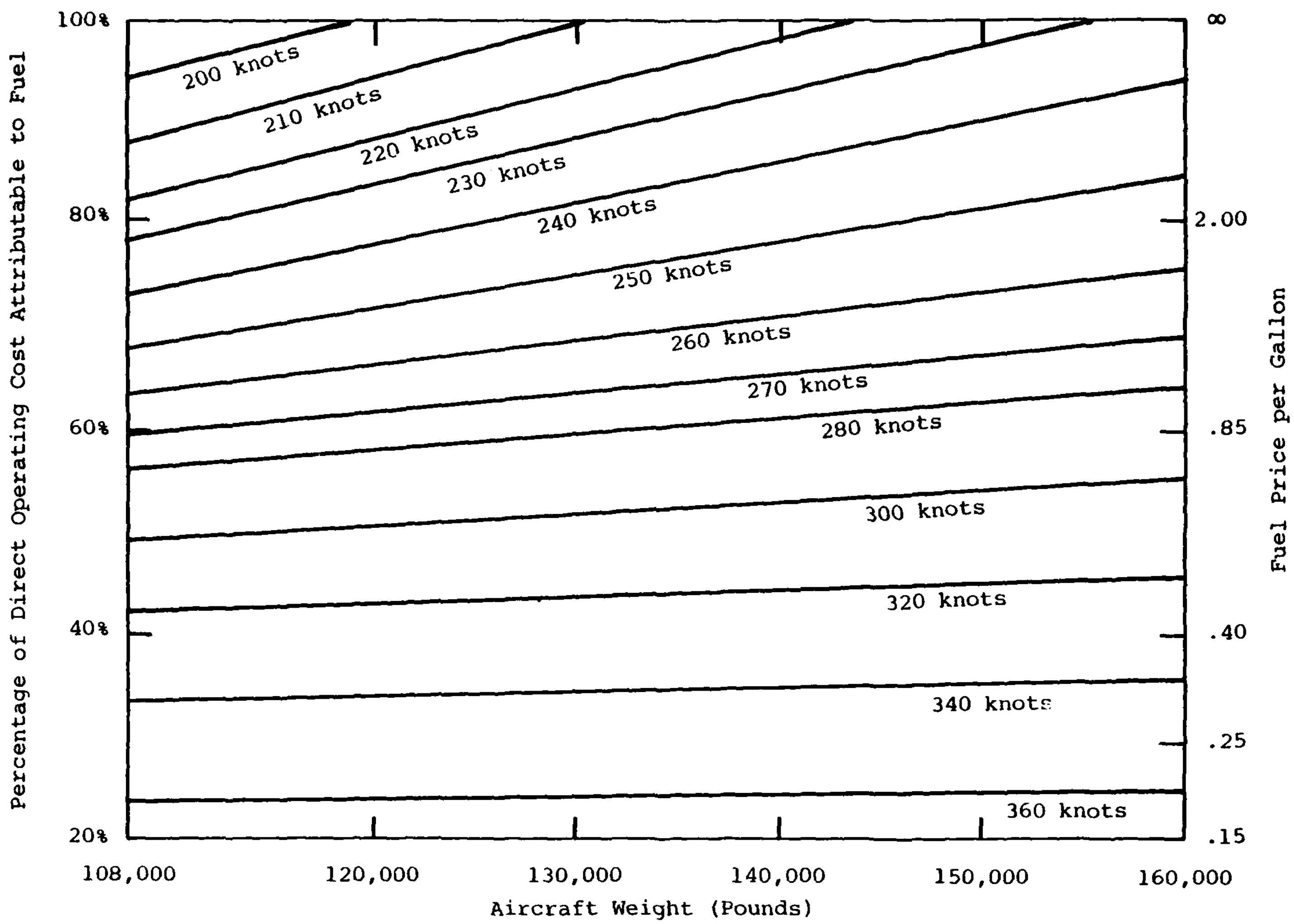

Figure 5-4. SENSITIVITY OF MINIMUM-COST DESCENT SPEED TO WEIGHT AND FUEL PRICE (727-200)

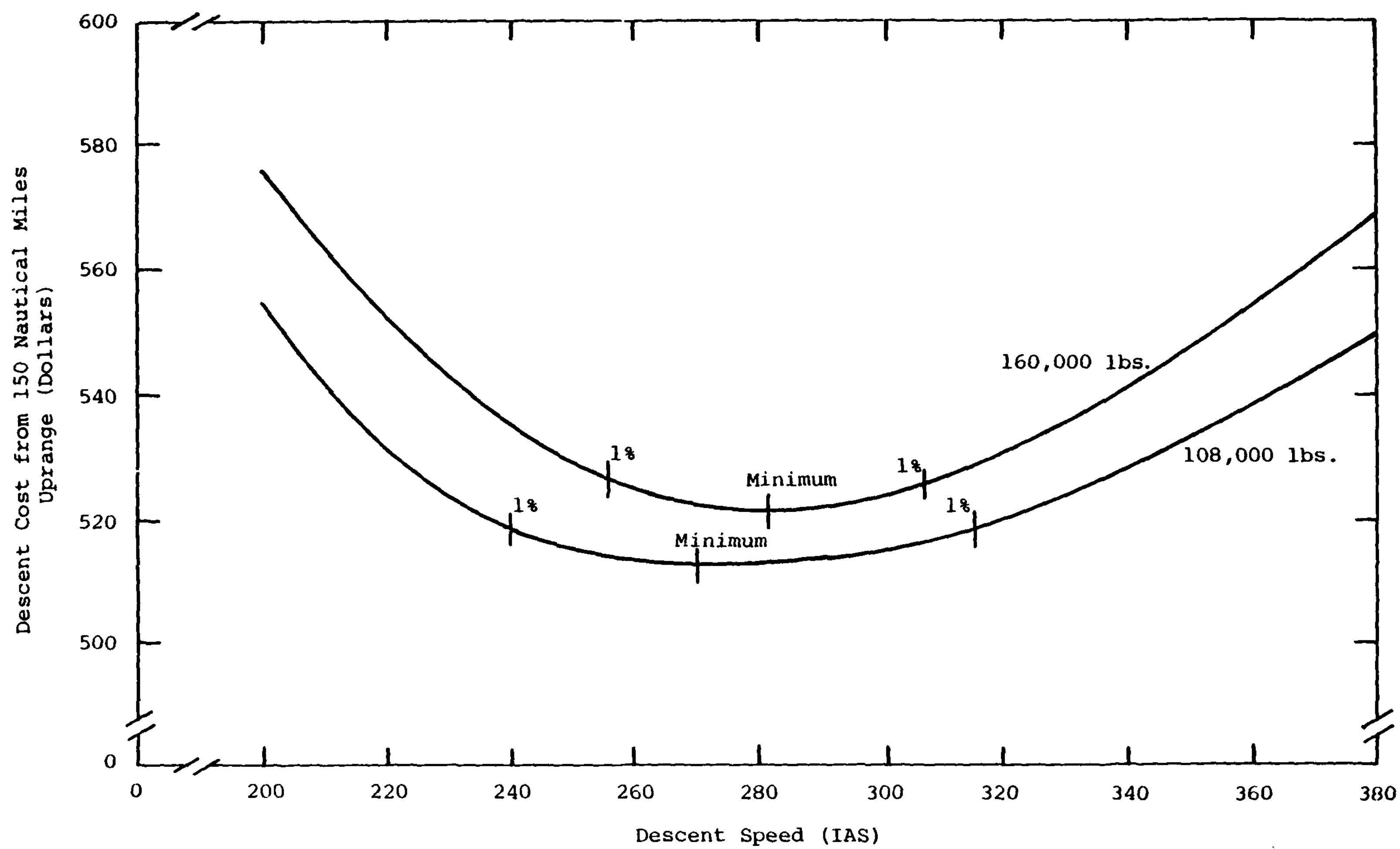

Figure 5-5. 727 SENSITIVITY OF DESCENT COST TO DESCENT SPEED

and absorbing the headwind at the phase of flight where it costs least. For a tailwind, the objective is to stay in the air longer and let the tailwind do as much of the work as possible. In coping with a strong headwind, the aircraft is limited by available power and increased drag due to high mach number. With strong tailwinds, the aircraft cannot profitably slow below the best hold speed. In some cases stall buffet margin may limit the attainable benefits from slowing to take advantage of a tailwind.

Figure 5-6 shows the relatively simple relationship between wind speed and best indicated descent airspeed. The wind speed shown in the graph is assumed to hold for all altitudes in the descent, although in reality, it usually varies greatly with altitude. Unless these variations are both large and predictable, it will be best to plan the descent on the basis of the average wind and to avoid changes in pitch during the descent. For tailwinds less than 20 knots and all headwinds, the proper airspeed adjustment is about 0.3 knot of speed change for each knot of wind. For stronger tailwinds the adjustment is about 0.25 knot per knot of wind. For winds of 80 knots or less the curves do not appear to approach the limits described above, which would cause a leveling of the curves at the left and right extremes.

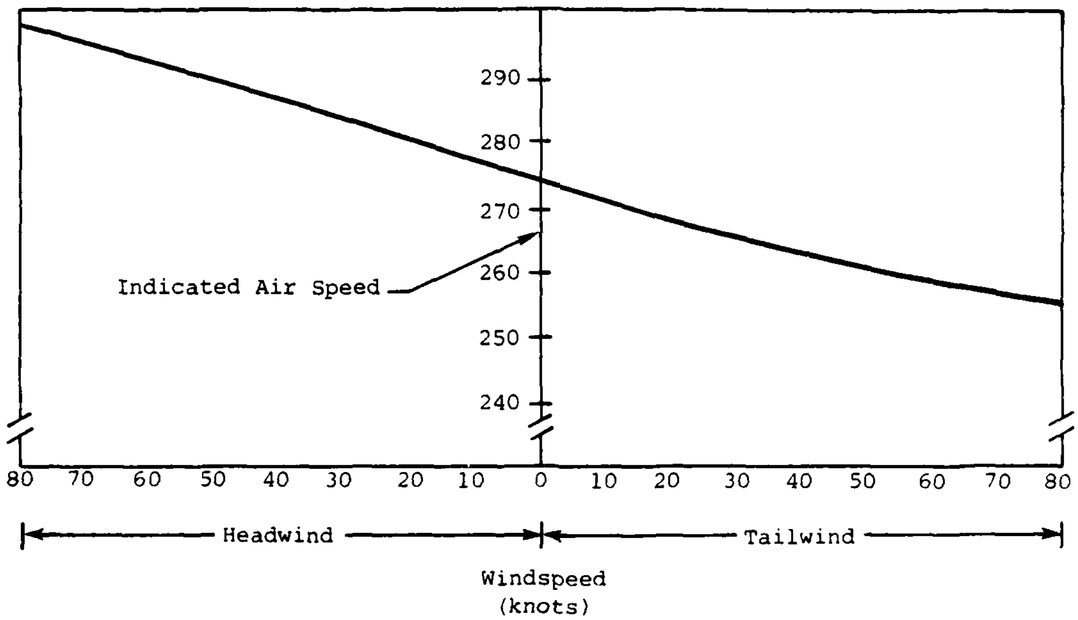

Figure 5-6. EFFECT OF WIND ON DESCENT PROFILE OF 727-200

5.3.6 Characteristics for Other Aircraft Types

Using the same method as for 727s, the best-descent airspeed for several aircraft types was calculated and plotted in Figure 5-7. For the A-300, L-1011, 747 and DC-9 it was necessary to calculate only the values for zero and 100 percent loading because the sensitivity to weight was so slight. The weights corresponding to empty or full loads varied by aircraft type, but in all cases the fully loaded weight was about 40 percent higher than the empty weight.

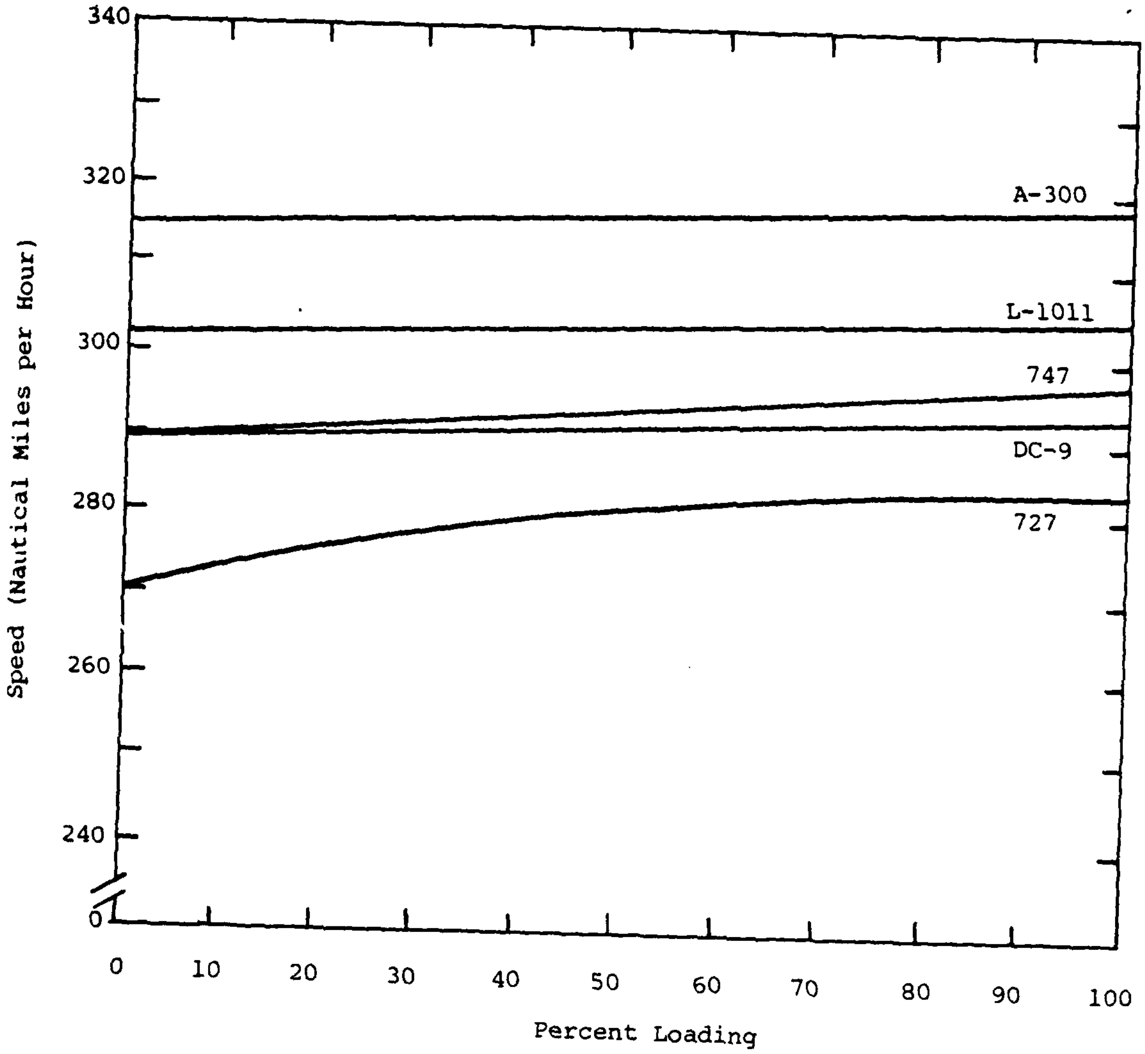

Figure 5-7. BEST AIRCRAFT DESCENT SPEEDS

While the speeds do vary among the aircraft types, there is little sensitivity to weight: optimal speeds vary at most 15 knots between empty and full loading. Sensitivity of cost to descent speed is also low for each of the aircraft types, as shown in Table 5-1. A uniform descent speed of 294 to 307 knots could accommodate all aircraft within 1 percent of the optimum descent cost. Although the best descent speeds for the 727 and A-300 are outside this range, the sensitivities are such that speeds between 294 and 307 knots are within 1 percent of optimum for these aircraft.

Table 5-1. SENSITIVITY OF DESCENT COST TO DESCENT AIRSPEED (150 MILES UPRANGE, 30,000 FEET ALTITUDE)

Aircraft - Loading	Best Speed (Knots)	1 Percent Higher Cost		2 Percent Higher Cost	
		Low	High	Low	High
727 - Empty	270	240	315	230	330
727 - Full	283	256	307	246	320
747 - Empty	289	264	321	254	340
747 - Full	300	270	338	259	351
L-1011 - Empty	302	278	340	267	358
L-1011 - Full	306	283	338	274	352
A-300 - Empty	315	290	347	281	360
A-300 - Full	320	294	355	284	370
DC-9 - Empty	289	262	318	250	329
DC-9 - Full	295	270	320	260	333

5.4 POINT-OF-DESCENT CALCULATIONS

Flying the minimum-cost descent speed is only half the battle in executing a profile descent. The other half is calculating the point at which to begin the descent. If it is begun too early, the aircraft will reach its final approach altitude (say 5,000 feet) too early. To make up for this, the pilot will have to cruise at a low altitude to cover the distance that should have been covered in cruise. On the other hand, if the descent is begun too late, the aircraft will cross the final approach fix too high and will have to bleed off the extra altitude either with speedbrakes or an early deployment of flaps or landing gear, or both.

Figure 5-8 shows the cost penalty for missing the optimum point of descent. These figures were calculated for a DC-10 with a gross weight of 320,000 pounds descending from 30,000 feet; figures for other aircraft types can be estimated on the basis of relative size. For an error on the early side, the airplane will be cruising at 5,000 feet at 270 KTAS (250 KIAS) and 49.1 pounds of fuel per nautical mile, instead of 30,000 feet at 454 KTAS and 31.2 pounds per nautical mile. Therefore, every mile for which the descent is begun too early costs 17.9 (49.1 - 31.2) pounds of fuel, and

$$\frac{1 \text{ nm}}{270 \text{ nm/hr}} - \frac{1 \text{ nm}}{454 \text{ nm/hr}} = 1.5 \times 10^{-3} \text{ hours}$$

which represents a total cost penalty of

$$17.9 \text{ lb.} \times \$.126/\text{lb} + 1.5 \times 10^{-3} \text{ hr} \times \$1,800 \text{ hr}$$
$$= \$2.26 + \$2.70 = \$4.96 \text{ per mile}$$

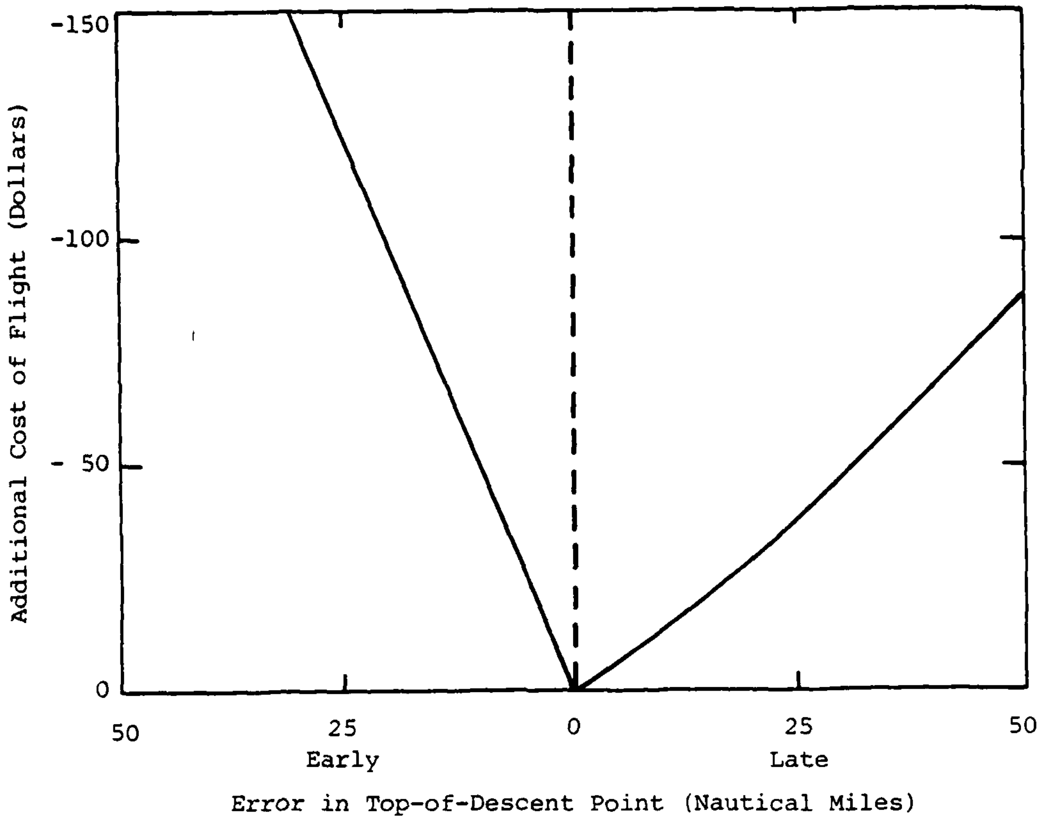

Figure 5-8. CONSEQUENCES OF ERROR IN CHOOSING TOP-OF-DESCENT POINT (DC-10, 320,000 POUNDS, DESCENDING FROM 30,000 FEET)

If the aircraft is late, the cost is primarily fuel. For every mile late, the aircraft will be burning 31.2 pounds of fuel at cruise power, instead of about 9.1 pounds that would have been burned over the same distance in an idle descent. Some time would be gained because of the substitution of fast high-altitude cruise for the relatively slow, low-altitude descent. For the purpose of estimating time savings from being late in starting descent it will be assumed that the additional cruise mileage at 454 KTAS substitutes for the deceleration to 250 KIAS at 10,000 feet. The aircraft will reach this altitude at about 334 KTAS. Therefore the cost penalty per nautical mile is 22.1 (31.2 - 9.1) pounds of fuel, plus

$$\frac{1}{454} - \frac{1}{334} = -7.9 \times 10^{-4} \text{ hours}$$

which is equivalent to

$$22.1 \text{ lb} \times \$.126/\text{lb} - 7.9 \times 10^{-4} \times \$1{,}800/\text{hr}$$
$$= \$2.78 - \$1.42 = \$1.36 \text{ per mile}$$

The time-related term will decrease to zero as the top-of-descent error increases, since the wasted cruise mileage substitutes for higher and higher airspeed portions of the descent. This accounts for the slight curvature in Figure 5-7. From the graph it can be observed that the cost penalty for being early is about three times the penalty for the same error on the late side. However, if the pilot begins the descent too early and realizes his mistake, he can minimize the penalty by adding power to slow the descent until the aircraft is back on the proper track. On the other hand, if he realizes he is late, nothing can be done because the extra fuel has already been burned.

The determination of the proper top-of-descent point depends primarily on the amount of altitude to be lost and the wind. As discussed in the last section, pilots should change their speed in the presence of wind. However, the magnitude of the compensation in knots of speed per knot of wind is less than one, so a headwind will result in a net decrease in groundspeed and an increase in the angle of descent, and vice-versa for a tailwind. Top-of-descent point changes about 0.3 nautical miles for each knot of wind aloft. For example, in descending with a 20-knot tailwind, the pilot would begin the descent 6.0 miles sooner (20 x 0.3). He would decrease his airspeed in descent by 6.0 (20 x 0.3) KIAS (about 8 KTAS). The net effect would be to increase groundspeed by 12 knots (20 - 8). These compensations assume no overriding ATC commands.

Other factors, such as weight and cruise airspeed, have less effect on the point of descent. According to the 727 descent profiles on which these data are based, descent for an empty aircraft from 30,000 feet would begin about 4 nautical miles later than for a fully loaded airplane. The final cruise speed prior to starting descent could also affect the point of descent or the descent profile since the aircraft would be starting from a different energy level.

5.5 DELAY MANAGEMENT

Profile descents into a terminal area are not always feasible because of delays. When the volume of incoming traffic exceeds runway capacity, delays inevitably develop. Further, as long as incoming volume is too high, the delays will become increasingly severe, cascading backward further and further from the terminal area and into en-route airspace.

In the current ATC environment, delays are managed by the controllers. A combination of vectors and speed change commands directed by the controller to the pilots will consume the delay and maintain separation. The vectoring could involve 360° turns, zigzag approaches, or other patterns. Mandated speeds might also be suboptimal from a fuel point of view.

When confronted with a known delay situation, the most desirable action on the part of the pilot is to slow down. But the aircraft can slow only so much before running into the risk of stalling. If the delay is bad enough, the pilot will have to slow down and fly extra distance to consume the delay. The pilot is often advised when he will be cleared to proceed with the approach and landing.

In this environment the trade-offs between time and fuel are no longer relevant because time is fixed by the length of delay. The only variable to be optimized is fuel consumption subject to the constraint of flight time. This is true regardless of the relative weight of time cost to fuel cost. The fuel-optimal flight profiles for management of ATC delays is an area in which little theoretical work has been done. A few limiting cases are presented in this section.

5.5.1 Small Delays

If a pilot expects no delay, he will typically fly a "long range" profile or slightly faster. This represents an optimal trade-off between time and fuel for that flight. It is about 1 percent less fuel-efficient and 3 to 6 percent faster than the fuel-optimal profile. Therefore, small delays on the order of 2 minutes per hour of remaining flight time or less will result in fuel savings, since they force the pilot to fly closer to the fuel-optimal speed. Of course, the pilot must be informed of the delay in time to make adjustments. In general, the more advance notice he gets, the smaller the fuel penalty will be. Even if the delay does result in fuel savings, the airline will have incurred the penalty of the time loss.

Longer delays will cost fuel. The pilot will be forced to back down the power curve between the fuel optimal point and the trough (Figure 5-9). The trough represents the speed at which fuel consumption per hour is minimized: the best hold speed. This is the speed at which the least power is needed to maintain altitude. If slowing to this speed will not consume the delay, the pilot must enter a holding pattern at that speed. Regardless of wind conditions, it is never efficient to go slower than the best hold speed. For most air carrier aircraft, this speed is slightly above the stall speed.

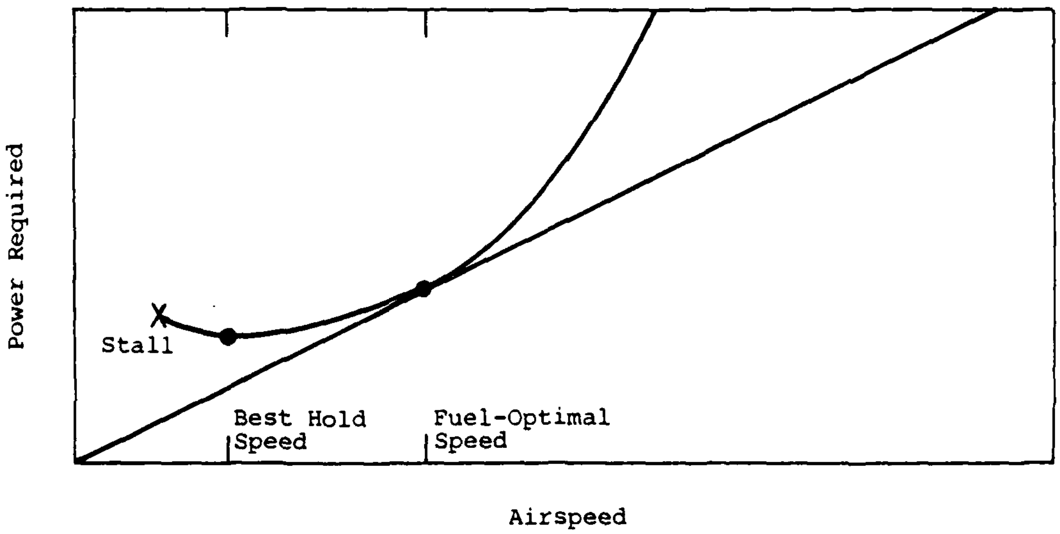

Figure 5-9. POWER CURVE

5.5.2 Endurance Descent

If the aircraft is at altitude when the pilot learns he must delay, he will, at the proper time, execute a maximum endurance descent. This is the speed which minimizes the descent rate in feet per minute. It results in a steeper angle of descent, but at a slower rate than the faster economy descent for maximum fuel mileage. The endurance descent is performed at idle thrust at a high angle of attack and would be used when the pilot must consume delay without regard for horizontal distance traveled. This is shown diagrammatically in Figure 5-10 for a 727-200 aircraft weighing 160,000 pounds.

5.5.3 Empirical Results

Typical airspeeds required to minimize the rate of descent are calculated from drag polar models assuming a linear relationship between lift and the angle of attack. As the aircraft approaches stall (i.e., high angle of attack), this relationship no longer holds. Therefore, it is possible that the speeds obtained this way may be below a prudent buffet margin for stall. The acceptable buffet margin, usually 1.3 g in smooth air, represents a limiting factor on the descent rate. If this limit applies, the pilot will be able to slow only to the minimum clean controllable airspeed or must deploy flaps to obtain the desired airspeed.

The curve in Figure 5-10 represents a locus of idle descent profiles. Points above the curve can be achieved by adding power; points below would require speed brakes. At higher altitudes the sink rate is higher, but fuel consumption per hour is much lower. The maximum endurance speed hardly varies with altitude at all. Theoretically, there is no variation; however, minor variations in idle thrust from low to high altitude cause a slight deviation. The curves shift left or right according to the square root of weight; thus, the minimum descent rate speed at 110,000 pounds would be approximately

$$188 \sqrt{\frac{110,000}{160,000}} = 156 \text{ KIAS}$$

The best indicated hold speed also varies with the square root of weight and not with altitude. However, fuel consumption per hour varies by altitude, as shown in Figures 5-11 and 5-12. Regardless of aircraft weight, the low point of the curve is about 25,000 feet. This was also found to be true for a 747 examined at light load (400,000 pounds gross weight) and heavy load (600,000 pounds). The best speeds at these weights were comparable to those of the 727. The sensitivity of fuel consumption to altitude in holding is, however, much less than the equivalent sensitivity in normal cruise. In holding, a 160,000-pound 727-200 can be at an altitude of anywhere from 15,000 to 35,000 feet with a maximum 3.3 percent difference in fuel consumption between the best and worst altitude. In normal cruise, the difference in fuel performance between 15,000 feet and 35,000 feet is about 30 percent. Thus, it is a misconception that hold altitude has an overwhelming impact on fuel consumption.

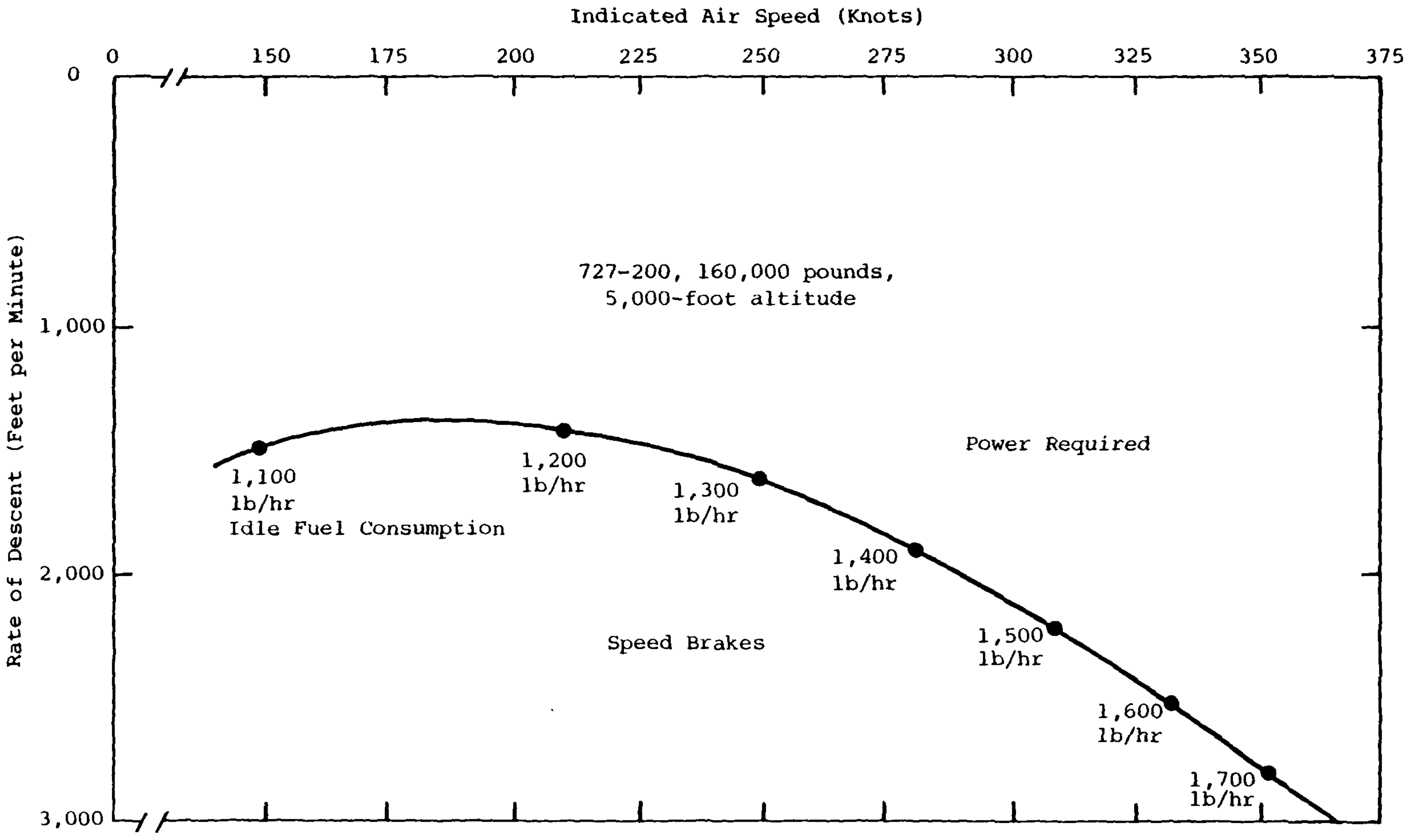

Figure 5-10. LOCUS OF IDLE THRUST DESCENT PROFILES

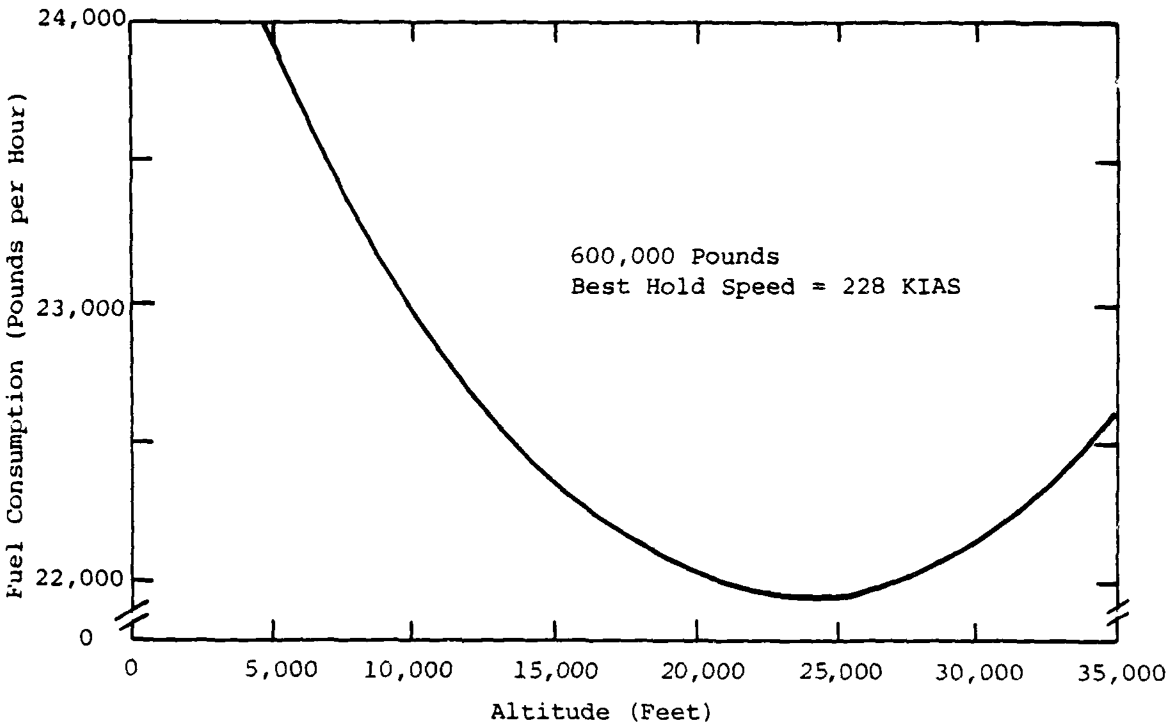

Figure 5-11. FUEL BURN RATES FOR HOLDING AT VARIOUS ALTITUDES AT BEST HOLD SPEED FOR 747

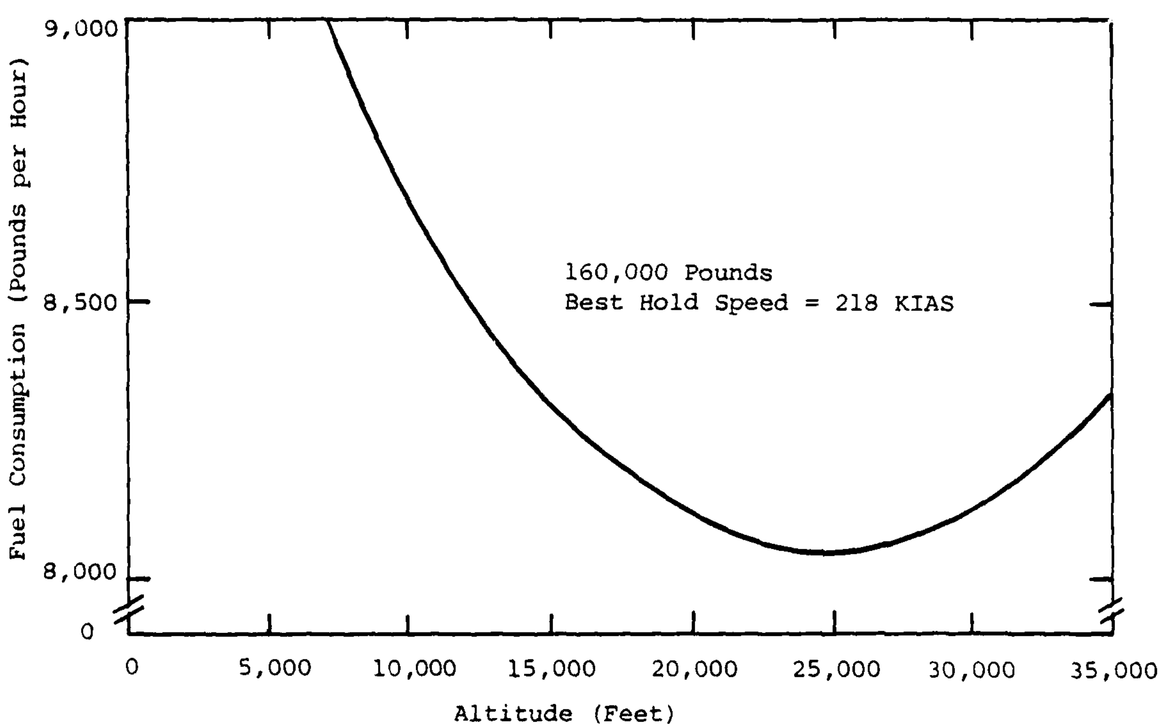

Figure 5-12. FUEL BURN RATES FOR HOLDING AT VARIOUS ALTITUDES AT BEST HOLD SPEED FOR 727-200

Thus in a long-delay situation, the pilot should execute a maximum endurance descent to 25,000 feet at 150 to 190 KIAS, depending on weight, as shown in Figure 5-10. He should hold there at 180 to 230 KIAS, as shown in Figure 5-11, until sufficient delay has been consumed to permit a second maximum-endurance descent to the airport traffic area.

5.6 EFFECTS OF ATC ON DESCENT PROFILES

The descent profiles presented in previous sections of this chapter have been developed on the assumption of a single airplane in the sky that could minimize its own costs without regard to anything else. In a real world, competition for airspace and ATC facilities will necessitate some compromises. While there will be some times when each airplane trying to land can get exactly the clearance it wants, there will be many more times when each airplane will have to settle for something less than ideal in order that all can be accommodated. This section examines some of these issues.

5.6.1 Descent Tracks

Normally, all incoming traffic is vectored over one or more approach fixes, where the traffic is sequenced for landing. Figure 5-13 shows the landing approach paths for runways 35L and 35R at Dallas/Fort Worth Airport. Traffic is routed over one of the four VORTACs, each about 30 miles from the runway. The traffic could have come from any of several en-route airways feeding into the VORTAC. Unfortunately, very few major hub airports have such a convenient array of VORTACs serving it in all directions at a convenient distance. In some cities, there are no VORTACs; in others, they are not at a uniform distance from the airport; in still others, terrain or noise considerations prevent the VORTACs from being used as efficiently as possible.

If all (or a majority of) traffic were RNAV-equipped, there would be no necessity to establish feeder fixes at VORs or at intersections, since any designated fix could be used. For example, a southbound aircraft could fly directly onto the downwind approach leg instead of being required to pass over the Bridgeport or Blue Ridge VORTAC. Admittedly, there are numerous operational problems with such a procedure; for example, the airspace north of the airport is likely to be reserved for departures. Although current ATC procedures are not set up for this kind of terminal navigation, the FAA might want to consider the benefits of having additional flexibility in assigning feeder fixes in the next generation of ATC computers. Such a scheme would allow pilots to reduce trip mileage and use less airspace.

Another problem in the vertical plane is that the approach fixes may be set up below the profile descent altitude for a point that far from the runway. This could happen if the airspace above the minimum altitude is used for en-route traffic. If this is the case, the net effect is the same as beginning a descent too early. The pilot will have to go into a low-altitude cruise or descend with partial power all the way to the outer marker.

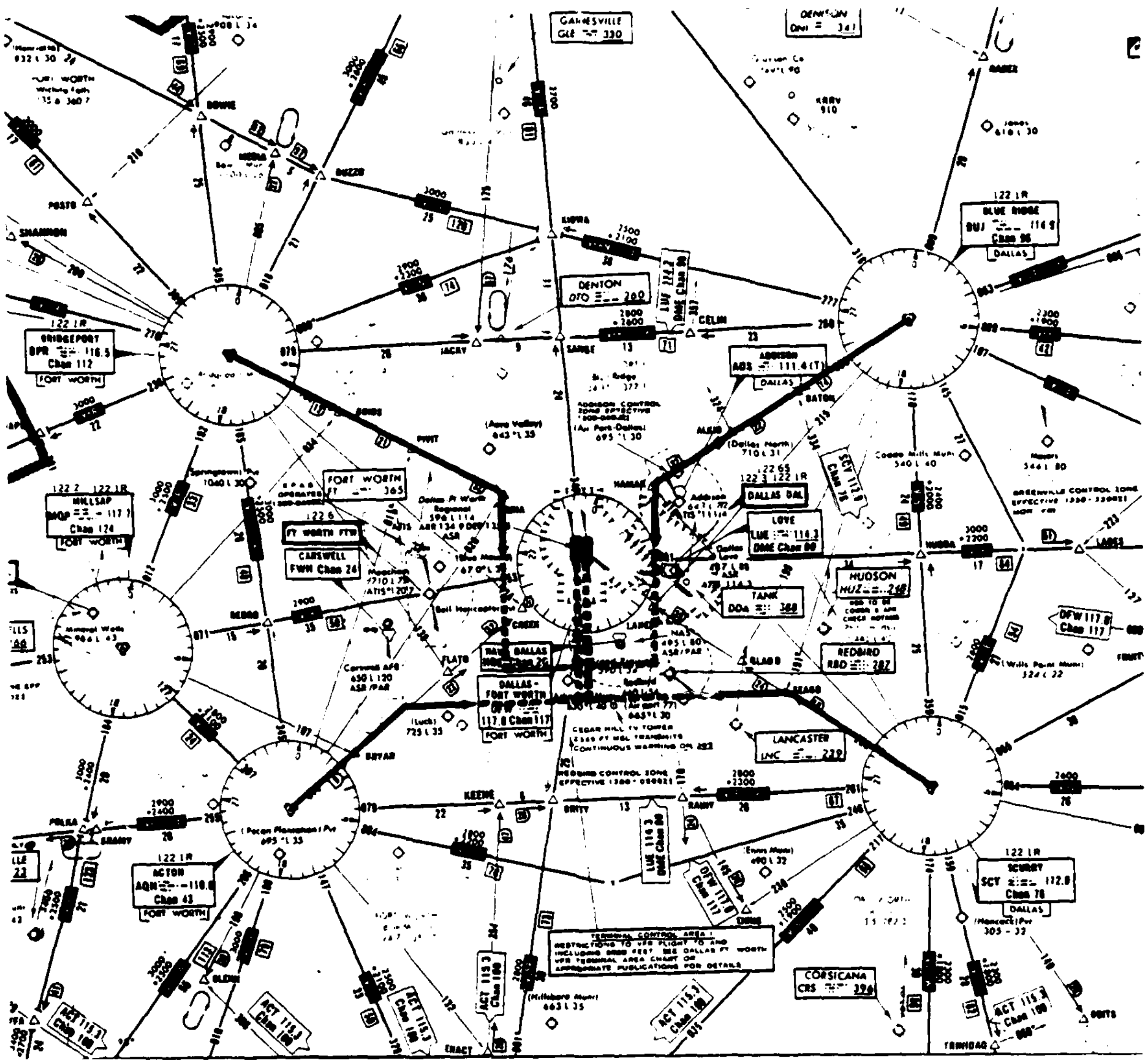

Figure 5-13. STANDARD DALLAS - FORT WORTH APPROACHES TO RUNWAYS 35L and 35R

5.6.2 Speed Controls and Speed Management Issues

By the time aircraft reach the final approach fix (usually a few miles uprange of the outer marker), they are all configured for landing and traveling at about the same speed. From that point back on the descent there is a possibility of significant speed variance among aircraft on the same track. If the faster airplane is in front, it might widen the separation to the point where a third aircraft could be safely fit between them: that is, a slot would be lost. If the slower aircraft is in front, a conflict could develop.

Normal variances in desirable descent airspeeds are discussed in Section 5.2, but this is not the whole story, as there are often overriding competitive considerations. For example, the pilot of aircraft A is anxious to get on the ground because he is running late and has a number of passengers who might miss their connecting flights. B, who is in front, is under no such pressure, but will probably choose to speed up his descent rather than have the controller vector A in front of him. Furthermore, if B's airline develops a reputation for always running a few minutes slower than A's, it could hurt B's business. In some cases, the controller may not have the flexibility to allow one aircraft to pass another and will therefore mandate a change in speed. These factors tend to reduce the otherwise large variance in descent speeds.

Where the lack of uniform speeds presents a problem, the burden to resolve the problems falls on the controller. One solution is simply to vector one or both of the airplanes onto parallel tracks so that the passing can proceed as shown in Figure 5-14. This requires sufficient time to the final approach fix so that this switch can be accomplished. Figure 5-15 shows the minimum distance required for overtaking to be accomplished as a function of the difference in speeds between the two aircraft. If there is not sufficient time, then the only alternative is simply to direct the overtaking aircraft to slow down, or direct the slow aircraft to speed up. Since the controller's job is easier with everyone going at about the same speed, and since airline pilots usually hate to see their competitor's airplanes overtake them in the approach pattern, the pilots will generally agree to conform to a standard to avoid being vectored or delayed by ATC. There is pressure to maintain uniform descent speeds, even when a different speed would be cost effective.

Where airspace permits, it might be effective to establish two separate tracks for "fast" and "slow" aircraft. In this way, pilots would not have to deviate as much from their preferred speed. There might be a willingness to detour an extra mile or two if it means that the aircraft can fly at its preferred descent speed without giving up its place in the sequence for landing.

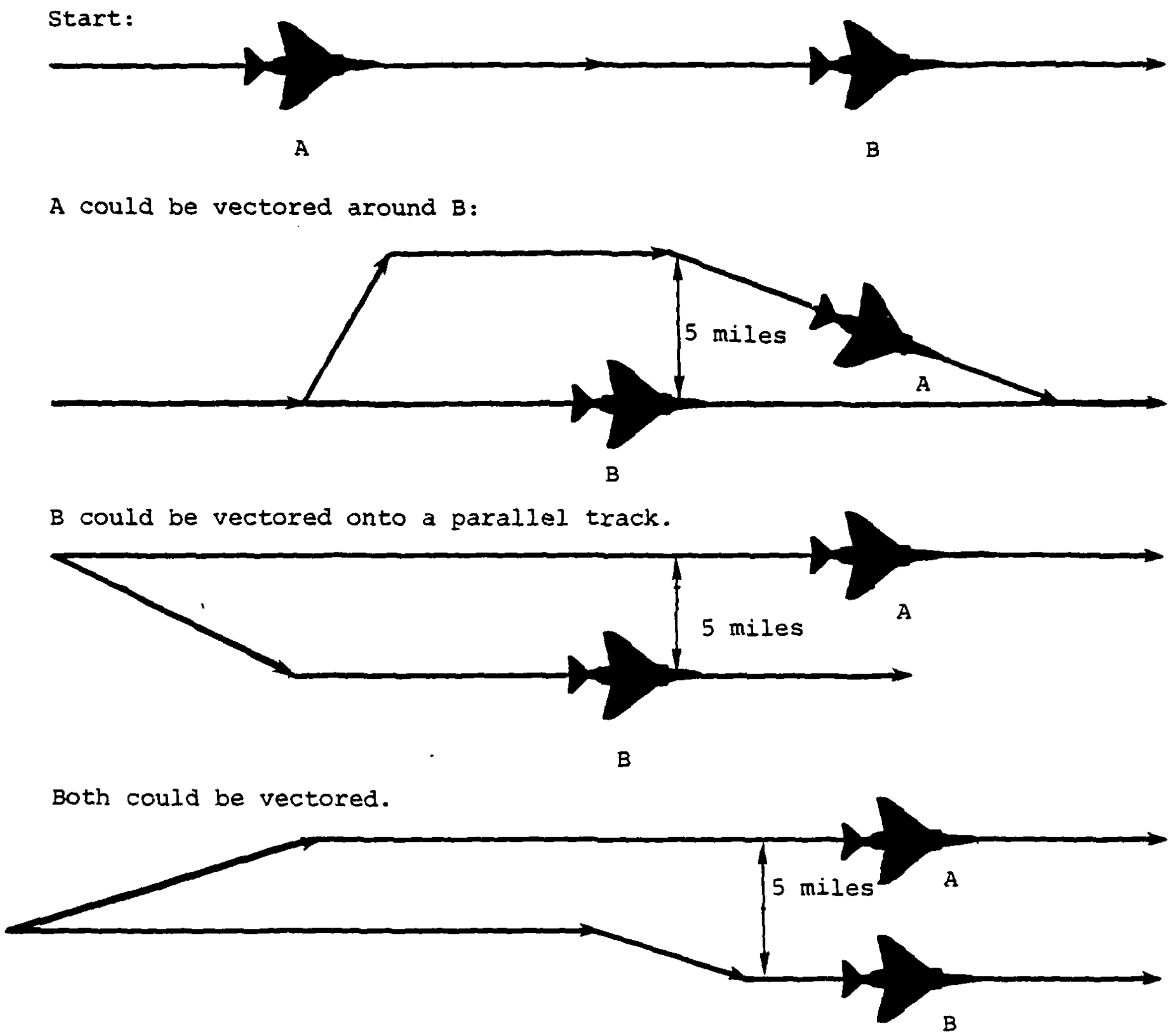

Figure 5-14. OVERTAKING AN AIRCRAFT ON A DESCENT TRACK

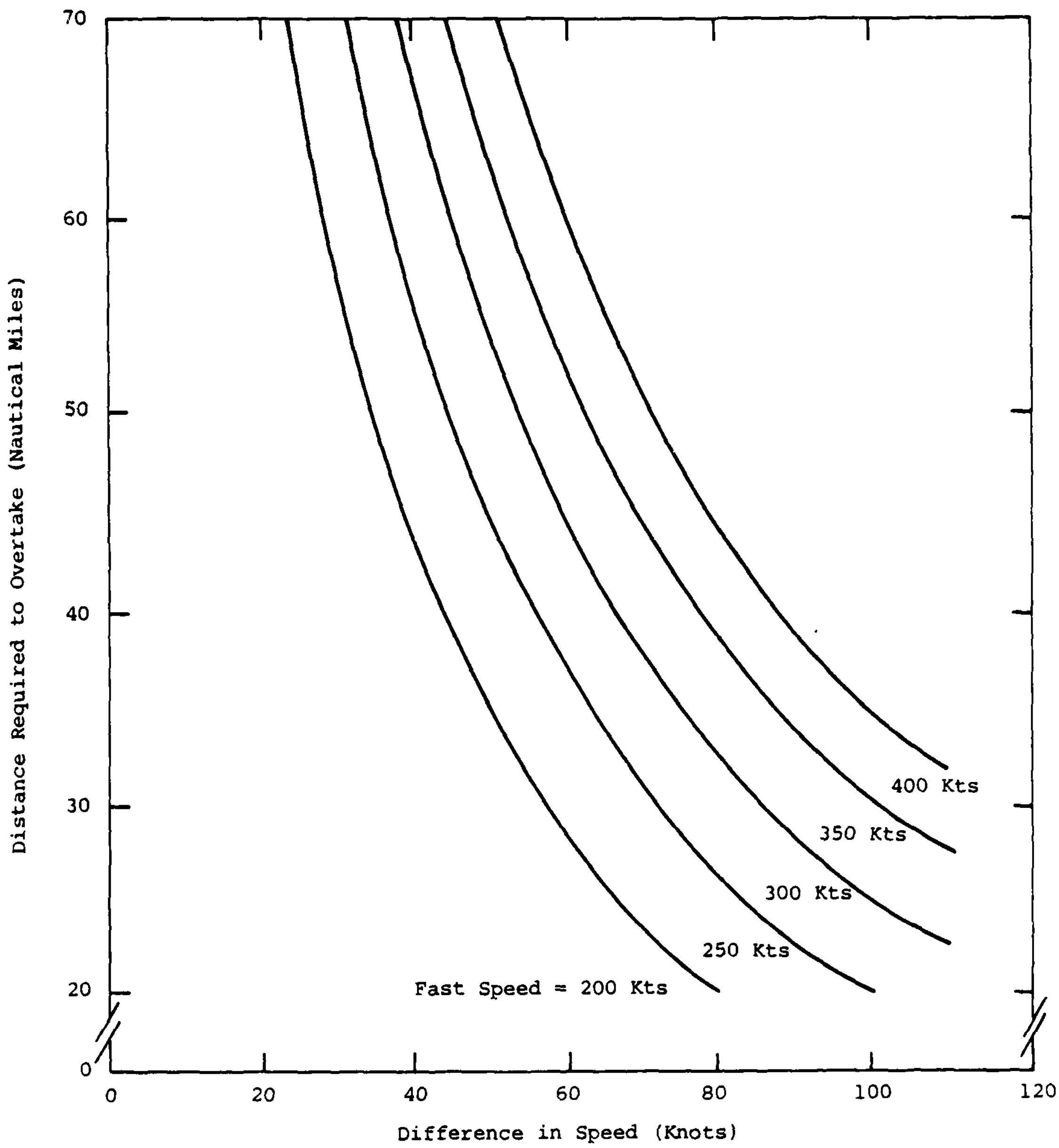

Figure 5-15. MINIMUM DISTANCE REQUIRED TO OVERTAKE SLOW AIRCRAFT, FIVE NAUTICAL MILE SEPARATION REQUIRED

CHAPTER SIX

ISSUES AFFECTING FMC USE

Flight performance is most likely to be limited by ATC constraints during the approach and landing phase. Traffic from the relatively roomy en-route sectors converges into a limited airspace. Runway throughput is limited by separation standards, which are in turn based on man-machine limitations. During busy periods, queues develop that must be managed within limited airspace. The pilot who attempts to use his FMC to conduct a profile descent from altitude under these conditions will more than likely be denied clearance to descend as he wishes. Or, if he is cleared, his descent may be interrupted by an ATC vector or mandatory speed change. This chapter examines this and other factors that might limit the effectiveness of FMCs, particulary in terminal areas.

6.1 CURRENT METERING PROCEDURES

The FAA plans to install metering software at 18 major hub airports over the next few years. Fourteen of these 18 airports show frequent large delays. The purpose of the metering program is to begin absorbing delay as far uprange as possible. Delays can be better managed in en-route airspace or in descent where there is still plenty of time to the runway. If an aircraft must be delayed after it arrives in the terminal area, there is no alternative to slowing to hold speed.

The metering system works as shown in Figure 6-1. As soon as an aircraft enters airspace for its last en-route ARTCC, it is eligible for metering. The system calculates an estimated arrival time at an approach fix known as a vertex. The time from the vertex to the runway is known. The vertex is a point near the runway beyond which no adjustments are possible; it may be the outer marker or runway threshold itself. Traffic is assumed to be fully sequenced on passing the meter fix, which is generally 30 to 50 miles from the runway. Vertex time is continuously updated until the aircraft passes the time parametric freeze point. At this point the estimated vertex determines the position in the first-come-first-served queue. Times are estimated to the nearest 0.01 minute to prevent ties from causing problems.

On the basis of an estimated time at the vertex, a meter fix slot time is assigned. The controller is responsible for ensuring that the airplane meets its slot time. His display tells him how much delay must be absorbed to

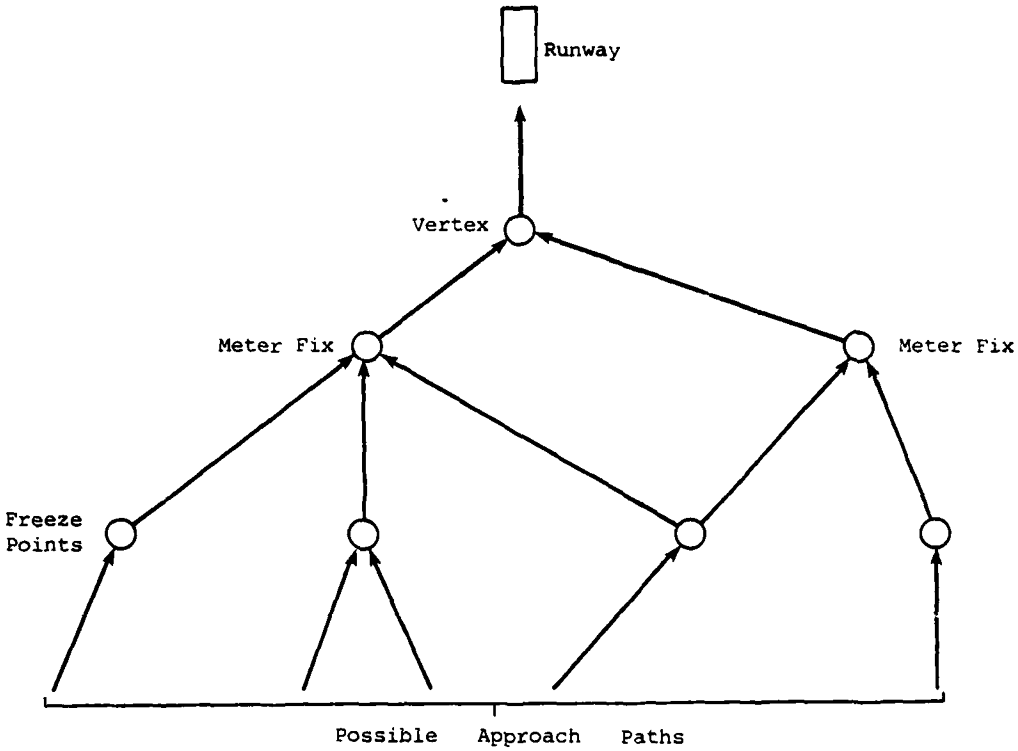

Figure 6-1. CURRENT METERING PROCEDURES AT LARGE HUBS

meet the assigned time. He can generate the delay with vectors, speed changes, or both. Slot times are computed on the basis of traffic flows through all vertexes feeding a particular runway. A controller could observe large gaps among slot times assigned to him because interleaving slots have been assigned to aircraft approaching the vertex from other meter fixes.

The result is that by the time the aircraft enters terminal airspace, much of the metering and sequencing work has been done. During peak traffic periods, this technique minimizes terminal-area traffic congestion without sacrificing any throughput. In addition, there should be some improvement in fuel performance, although the system was not designed for this purpose.

6.2 EXTENSION TO 4-D AIR TRAFFIC CONTROL

The metering system described in Section 6-1 is, in effect, a manual 4-D ATC system with the ATC computer assigning slot times and the controller ensuring that aircraft meet those times. An FMC-equipped aircraft would have the capability of meeting its slot time all by itself, with little or no assistance from the controller. This offers potential flexibilities in assigning vertex points and might free up some controller time that could be used to handle additional traffic. However, there will be some problems. Aircraft will not always make their assigned times, and in long-delay situations when they must deviate from a direct flight path, it will be necessary to give the aircraft conflict-free flight paths to follow in using up the assigned delay.

In an operational 4-D ATC system, several factors might prevent pilots from meeting assigned slot times within required tolerances. One factor is the limitations of the FMC equipment. All on-board computers would be able to calculate and recalculate the proper speed to meet a 4-D waypoint, but advisory systems would not have the closed loop control of the aircraft necessary to ensure success. The ability to make assigned time would then boil down to the ability of the pilot to fly the assigned profile accurately. Another factor is the lack of accurate wind data downrange. Presence of wind shear or turbulence could force rapid compensations in airspeed to keep the aircraft on trajectory to meet the assigned waypoint time. In an advisory system, the pilot can, to some extent, compensate for these errors by changing speeds abruptly. However, if he makes the assigned time by going at a very slow or fast speed necessitated by unforeseen conditions, he will probably need further speed corrections after passing the waypoint. Fuel consumption undoubtedly would suffer as well. Thus, the sophistication of the FMC equipment will in large part determine the ability of the aircraft to meet its assigned time. Lower mean errors can be expected from higher capability aircraft.

Even if everyone could guarantee to meet his assigned time exactly, there would still be the problem of assuring that no conflicts would exist anywhere in the airspace at any time. This is an ATC function. For small delays, the computer could assume a direct trajectory to the waypoint, but if any minimum holding speed were required, a flight path would have to be assigned that would be conflict free and still pass through the assigned 4-D waypoint. This would require some type of data exchange between the ATC computer and the FMC. In the manual metering system, the controller chooses a path himself and assigns it to the aircraft; if conflicts subsequently develop, the controller then resolves them by appropriate action.

An automated system could provide metering and spacing and use a data link so that neither pilot nor controller would be directly involved. The FMC could communicate its desired slot time well in advance, while the ATC computer would receive requests from other aircraft in the area as well. At the appropriate time, it would assign slot times and a flight path to meet those times and transmit them by data link. It is hoped the assigned time would be very close to the aircraft's desired time. The FMC would accept the command and store the path in its memory. Exceptions or deviations would be handled by voice communication between pilot and controller.

A fully automated system would still have to accommodate non-equipped IFR aircraft. If the majority of aircraft are equipped, the non-equipped minority can probably be worked in at some cost in controller workload. On the other hand, if the majority are not equipped, benefits may be zero or even negative since the sparse level of capability could cause more problems than it would solve. The percentage of aircraft equipped with FMCs may be expected to rise sharply in the next few years as airlines phase in new equipped aircraft and retrofit others. This percentage will vary not only by aircraft type but also by airport. For the high density major hub airports, where delays cause the most problems, the percent of equipped aircraft will vary according to the type of traffic coming into each airport. This is the subject of the next section.

6.3 FORECAST PERCENTAGE OF FMC-EQUIPPED AIRCRAFT OPERATIONS

To achieve maximum benefit from 4-D navigational systems, major modifications to the air traffic control system will be required. Even then, the program would not likely be effective until the majority of aircraft operating at major hubs have a 4-D capability. By the late 1980s, the percentage of air carrier aircraft with some sort of flight management capability is expected to reach 70 to 80 percent, probably high enough to accrue significant benefits from the use of 4-D at high density airports. Depending on the mix of traffic at the airport, however, the percentage of operations that could be handled with such a system might vary considerably. This section investigates this issue for the twenty-five busiest major hub airports in the late 1980s.

6.3.1 Aircraft Fleet Trends

World Aircraft Forecast to 1980 (Reference 15), provides a forecast for the United States air carrier fleet for 1979 through 1988. The forecast includes all turbofan and turbojet aircraft and is broken down by aircraft type. The data are presented in Table 6-1.

The data project the demise of the 707s, BAC-111s, Convair 580s, and Falcon 20s. It also shows the peaking and gradual replacement of the 727s, 737s, DC-8s, and early-model DC-9s. The early 80s sees the introduction of the new-technology aircraft: the A300 series, the 757, 767, DC-9-80, and L-1011-500. In addition, many forecast aircraft have yet to be specifically identified. Those aircraft are assigned functional identifiers on the basis of typical ranges and seating densities. The functional identifiers associated with those categories are described at the bottom of Table 6-1. It is presumed that those aircraft-to-be-named-later would replace aircraft currently operating on routes of a particular traffic density and haul length, even though airplane manufacturers have not yet committed themselves to produce them.

6.3.2 Traffic Trends

Traffic for the twenty-five busiest hubs (selected by number of air carrier operations in 1979) has been forecast for 1979 through 1988.* The data are summarized in Table 6-2. The table indicates that one airport is reducing operations (DCA) and three others have limited future growth due to capacity constraints and the availability of reliever airports in those

* Reference 29.

Table 6-1. FORECAST AIR CARRIER FLEET BY AIRCRAFT TYPE -- 1979 THROUGH 1988

AIRCRAFT TYPE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
707-100	70	63	53	48	44	33	4	3	0	0
707-320	120	112	98	89	78	60	44	11	1	1
707-720B	9	4	0	0	0	0	0	0	0	0
727-100	376	331	299	192	116	86	76	70	70	70
727-200	648	723	779	811	823	786	728	644	606	576
737-200	195	208	217	220	223	181	135	110	106	100
747	91	94	97	100	100	100	100	100	98	52
747-SP	12	17	20	23	23	23	23	23	23	23
747-F	23	26	26	26	26	26	26	26	26	25
757	0	0	0	0	11	21	33	45	45	45
767-200	0	0	0	18	59	96	128	155	161	161
DC-8	39	33	28	24	13	13	13	11	11	11
DC-8-60	85	87	84	82	80	72	69	68	62	53
DC-8-F	40	40	40	37	35	26	26	20	12	4
DC-9-10/20	79	76	72	49	38	35	35	33	30	25
DC-9-30/40	268	287	299	302	285	244	182	142	126	126
DC-9-50	56	60	62	62	62	62	62	62	62	62
DC-9-80	0	8	20	26	26	26	26	26	26	26
DC-10-10	104	114	123	126	129	129	129	129	129	129
DC-10-30	13	19	20	21	22	22	22	22	22	22
DC-10-40	22	22	22	22	22	22	22	22	22	22
BAC-111	30	26	12	0	0	0	0	0	0	0
CV-580	27	24	16	13	7	0	0	0	0	0
A300B	12	17	22	23	23	23	23	23	23	23
FAL20	33	33	33	33	33	30	18	0	0	0
L-1011	82	82	85	87	87	87	87	87	87	81
L-1011-500	2	9	18	25	32	32	32	32	32	32
SR-C	0	0	0	0	0	1	5	10	10	14
MR-C	0	0	4	8	18	27	34	42	45	61
LR-C	0	0	2	3	6	8	14	21	26	34
SR-LD	0	0	1	2	20	26	55	63	80	89
SR-MD	0	0	0	0	5	14	19	27	27	35
SR-HD	0	0	0	6	15	49	95	131	138	153
MR-LD	0	7	21	58	89	89	132	150	181	218
MR-MD	0	0	0	6	7	8	30	37	62	109
MR-HD	0	0	0	10	22	37	78	104	114	137
LR-LD	0	0	0	0	1	1	1	1	2	2
LR-HD	0	0	6	10	10	15	22	27	33	67
LR-MD	0	0	9	11	28	44	72	82	99	189
TOTAL	2436	2522	2588	2573	2618	2554	2600	2559	2597	2777

Legend:

SR-C -- Short Range-Cargo: Range less than 800 nautical miles, 17 to 22 tons cargo

MR-C -- Medium Range-Cargo: Range between 800 and 2400 nautical miles, 45 to 55 tons cargo

LR-C -- Long Range-Cargo: Range more than 2400 nautical miles, 100 to 110 tons cargo

SR-LD -- Short Range-Low Density Seating: 120 seats

SR-MD -- Short Range-Medium Density Seating: 160 seats

SR-HD -- Short Range-High Density Seating: 180 seats

MR-LD -- Medium Range-Low Density Seating: 160 seats

MR-MD -- Medium Range-Medium Density Seating: 210 seats

MR-HD -- Medium Range-High Density Seating: [illegible]70 seats

LR-LD -- Long Range-Low Density Seating: 150 seats

LR-MD -- Long Range-Medium Density Seating: 270 seats

LR-HD -- Long Range-High Density Seating: 420 seats

Table 6-2. TERMINAL AREA FORECAST

Hub		1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
ORD	Chicago	605	611	612	613	614	615	616	617	618	618	619
ATL	Atlanta	497	509	523	537	551	565	579	588	596	604	613
LAX	Los Angeles	379	382	382	383	384	385	385	386	387	388	388
DFW	Dallas/Fort Worth	323	334	341	348	355	362	368	375	382	389	396
JFK	New York-Kennedy	285	294	300	305	313	319	324	330	338	344	349
DEN	Denver	297	325	334	342	350	359	367	372	377	381	386
LGA	New York-LaGuardia	270	273	275	305	280	283	285	288	290	293	295
SFO	San Francisco	274	281	282	342	284	284	285	284	283	281	280
MIA	Miami	259	273	276	278	281	284	287	290	293	296	299
BOS	Boston	225	231	235	240	246	250	255	259	266	270	274
DCA	Washington, D.C.	202	197	193	187	181	175	175	175	175	175	175
PIT	Pittsburgh	201	207	211	216	221	225	230	234	238	242	247
STL	St. Louis	198	205	207	208	210	211	213	214	216	217	219
DTW	Detroit	181	198	201	205	211	214	218	222	227	231	235
IAH	Houston	166	170	175	180	184	189	194	198	203	207	211
PHL	Philadelphia	147	147	150	154	158	162	166	170	175	179	184
MEM	Memphis	153	164	167	170	174	178	181	184	188	191	194
EWR	New York-Newark	137	141	144	147	151	153	156	159	163	165	168
CLE	Cleveland	136	141	142	144	146	148	150	152	155	158	161
TPA	Tampa	135	141	144	148	151	154	157	160	163	167	170
MSP	Minneapolis	144	161	164	167	171	174	177	180	185	188	191
MCI	Kansas City	130	137	140	143	146	150	153	155	157	160	162
SEA	Seattle	129	140	144	147	150	153	157	159	162	165	167
HNL	Honolulu	125	131	133	135	137	139	141	143	145	147	149
LAS	Las Vegas	124	134	136	139	143	145	148	150	154	157	159

cities (ORD, LAX, and SFO). Two other airports show growth well below average (LGA, STL) for similar reasons. The average growth currently forecast for all major hubs during that period is approximately 15.6 percent. The data include both foreign and domestic air carrier operations.

6.3.3 Method for Projecting Percent of Aircraft Equipped with FMCs at Major Hubs

As far as could be determined, there is no current forecast for percent of FMC-equipped operations at major hubs. Therefore, a method was developed for producing the forecast from existing data. The available data come from three sources: (1) the *DMS World Aircraft Forecast to 1988* (Table 6-1), (2) the *Airport Activity Statistics for Calendar Year 1979* (which contains the number of U.S. air carrier operations, by hub by aircraft type for 1979 only), and (3) the *Terminal Area Forecasts for Fiscal Years 1980-1991* (Table 6-2). Also used is the forecast of percent of aircraft equipped with FMCs by aircraft type (Table 2-2), which is based on discussions with the FMC manufacturers and airlines.

These sources do not, however, contain all of the data needed to produce the forecast of the percent of FMC-equipped operations by airport. Certain elements need to be derived and several assumptions are required. Figure 6-2 illustrates the three-dimensional matrix that must be filled in. Each data element corresponds to the number of U.S. air carrier operations for a particular hub, aircraft type, and year. The data bases available are, at best, two-dimensional slices of the desired result. Therefore, the task boils down to projecting the available data into the three-dimensional matrix in such a way that the projections are consistent with the given set of data and forecasts.

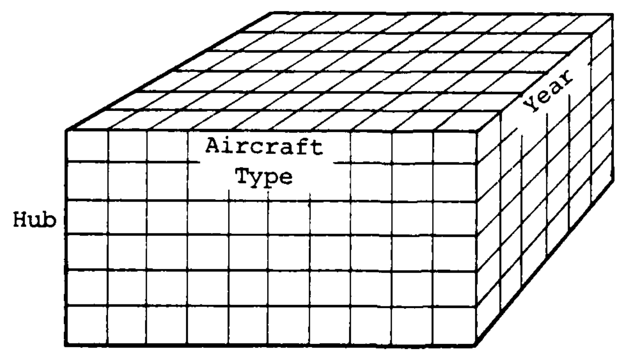

Figure 6-2. THREE-DIMENSIONAL OPERATIONS MATRIX

The first step was to project the number of U.S. air carrier operations (N) for a given aircraft type, hub, and year. A preliminary estimate was obtained by assuming that the proportion of operations taken by each aircraft type was constant over ti. This will be revised later to take into account new-technology aircraft. The following relationship was used:

$$\frac{N}{\text{Total operations for given hub for given year}} = \frac{\text{Number of operations for given aircraft type for given hub for base year}}{\text{Total operations for given hub for base year}}$$

The relationship was established for the calendar year 1979 for each of the top 25 hubs, ranked according to total air carrier operations, as obtained from *Terminal Area Forecasts* (Reference 28). These forecasts provided the projected number of operations for all aircraft types by hub, but the forecast is based on the fiscal year and therefore had to be adjusted to represent the calendar year. To do this, one quarter of the next year was averaged into three quarters of the current year.

In addition, the data were normalized to be consistent with the base year data extracted from the airport activity statistics. This was required since the terminal area forecast includes foreign flag air carrier operations. It was assumed that the ratio of foreign to U.S. air carrier operations will remain constant over the forecast period. The resulting traffic forecast appears in Table 6-3. Subsequent calculations are based on the data in this table.

The relationship further assumes that an increase or decrease in operations at a hub is distributed proportionately among the aircraft operating at that hub in the base year. It implicitly assumes that there is no change in the fleet mix. However, the fleet mix does change and N needs to be modified to account for this. To compensate for those changes in the existing fleet, the following relationship is used:

$$N_1 = N \times \frac{\dfrac{\text{Number of aircraft for a given aircraft type for a given year}}{\text{Total fleet for that year}}}{\dfrac{\text{Number of aircraft for a given aircraft type for the base year}}{\text{Total fleet for the base year}}}$$

This will decrease or increase the number of operations for each of the aircraft types, for each hub and for each year, according to the share of the fleet associated with that aircraft type. It assumes that a fleet change for a particular aircraft type is reflected proportionately among those hubs whose operations included that aircraft type.

This step compensates for the fleet mix change associated with present-technology aircraft. It will not work for new-technology aircraft because there currently are no new-technology operations. (Both N and the denominator of the ratio are zero.) To include these new-technology aircraft

Table 6-3. TRAFFIC TRENDS 1979-1988*				
Hub		Total Operations 1979	Total Operations 1988	Percentage Change
ORD	Chicago	562,337	572,518	1.8
ATL	Atlanta	519,406	629,510	21.2
LAX	Los Angeles	381,626	389,652	2.1
DFW	Dallas/Fort Worth	324,959	389,746	19.9
DEN	Denver	296,296	372,311	25.7
JFK	New York-Kennedy	175,460	210,908	20.2
SFO	San Francisco	240,306	244,649	1.8
LGA	New York-LaGuardia	232,079	251,771	8.5
MIA	Miami	189,984	214,539	12.9
BOS	Boston	192,778	230,137	19.4
DCA	Washington, D.C.	207,844	180,954	-12.9
PIT	Pittsburgh	186,373	223,089	19.7
STL	St. Louis	197,569	215,345	9.0
DTW	Detroit	181,823	228,006	25.4
IAH	Houston	168,179	209,459	24.5
MEM	Memphis	128,550	158,208	23.1
PHL	Philadelphia	149,278	182,779	22.4
MSP	Minneapolis	150,104	191,678	27.7
EWR	New York-Newark	116,039	139,576	20.3
CLE	Cleveland	127,968	148,510	16.1
TPA	Tampa	126,888	155,589	22.6
MCI	Kansas City	128,824	157,120	22.0
SEA	Seattle	121,944	153,346	25.8
HNL	Honolulu	96,378	112,308	16.5
LAS	Las Vegas	124,129	154,446	24.4
Total		5,327,141	6,116,154	14.8

*Includes fiscal year adjustments and eliminates foreign carrier influences.

operations, it is necessary to first compute the number of operations that are no longer accounted for (i.e., due to the replacement of some of the present-technology aircraft - 707s, BACs, Falcons, etc). These operations are distributed equally (by hub) among the new-technology aircraft in the same proportion as their numbers in the new-technology fleet. The relationship is expressed as follows:

$$\frac{N_2}{\text{Total new-technology aircraft operations for given hub for given year}} = \frac{\text{Number of given new-technology aircraft in fleet in that year}}{\text{Total new-technology aircraft for that year}}$$

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where N_2 is the number of new-technology aircraft operations for a given new-technology aircraft type, given hub and year.

The equal distribution of new-aircraft operations among hubs seems to be an arbitrary assumption, but it is necessitated by a lack of data forecasting how these aircraft will be distributed throughout the system. The answer to this question in turn depends on the route structures of the airlines buying these aircraft. Examining the problem at this level would have greatly increased its complexity, and it was believed not to be worthwhile. Therefore, it is reasonable to say that the operations estimates, by aircraft type by hub, could be in error by several percentage points.

6.3.4 Results and Discussion

The last step has produced a matrix of aircraft operations forecast for 1979 through 1988, separated by aircraft type and hub. The data are consistent with existing operations and fleet forecasts. To determine the number of operations associated with FMC-equipped aircraft, data on forecasts of aircraft equipped with FMCs (Section 2.6) were applied for each aircraft type to obtain the overall percentage of operations at each major hub having 4-D capability. Overall results appear in Table 6-4.

The table shows the estimate that at the top 25 major hubs, the percentage of operations in 1988 with some flight management capability will vary from 66 to 86 percent with an average of 79 percent. The airports with the highest percentages of FMC equipment are the major coastal international gateway airports, such as John F. Kennedy, Miami, Los Angeles, and San Francisco. Those airports have the highest percentage of wide-body operations. Their domestic routes tend to be high-density long hauls as well. The airports with low percentages tend to be domestic regional hubs, such as Pittsburgh and St. Louis. These cities serve as regional feeders. Their high-density traffic is a smaller percent of their total; hence, their FMC-equipped aircraft percentages are lower. In between are cities such as Atlanta, Chicago, and Denver, which exhibit characteristics of both groups.

Honolulu is a somewhat anomalous case. Traffic into Honolulu is either high-density, long-haul traffic from either the mainland or the Far East, or it is short-haul, low-density, high-frequency interisland traffic. Because of its location there can be nothing in between. There is little, if any, scheduled 727 service in the Hawaiian Islands at this time. The unusual mix of traffic results in the low percentage.

Another hub for which the output data might be suspect is Washington National Airport. Restrictions on the type of traffic that can operate there and limits on the number of air carrier operations have resulted in an unusual traffic mix. The absence of wide-body operations makes it likely that it will have a much lower percentage of FMC-equipped operations than the 78 percent estimated by the method explained in Section 6.3.3. The estimation algorithm is blind to the kind of regulatory constraints that exist there.

Table 6-4. PERCENT OF AIRCRAFT EQUIPPED WITH FMCs AT MAJOR HUBS IN 1988				
Hub		Number of Operations: All Aircraft	Number of Operations: FMC-Equipped Aircraft	Percent of Total Operations
ORD	Chicago	572,518	468,673	82
ATL	Atlanta	629,510	482,814	77
LAX	Los Angeles	389,652	336,374	86
DFW	Dallas/Fort Worth	389,746	318,819	82
DEN	Denver	372,311	302,864	81
JFK	New York-Kennedy	210,908	181,844	86
SFO	San Francisco	244,649	206,895	85
LGA	New York-LaGuardia	251,771	201,062	80
MIA	Miami	214,539	177,247	83
BOS	Boston	230,137	190,149	83
DCA	Washington, D.C.	180,954	140,336	78
PIT	Pittsburgh	223,089	163,693	73
STL	St. Louis	215,345	161,469	75
DTW	Detroit	228,006	172,526	76
IAH	Houston	209,459	164,335	78
MEM	Memphis	158,208	115,712	73
PHL	Philadelphia	182,779	144,050	79
MSP	Minneapolis	191,678	146,210	76
EWR	New York-Newark	139,576	112,956	81
CLE	Cleveland	148,510	116,785	79
TPA	Tampa	155,589	124,018	80
MCI	Kansas City	157,120	129,449	82
SEA	Seattle	153,346	128,948	84
HNL	Honolulu	112,308	74,524	66
LAS	Las Vegas	154,446	117,909	76
All 25 Hubs		6,115,964	4,879,661	79

6.4 ATC ISSUES TO BE RESOLVED

Minimizing operating costs in terminal areas, particularly fuel costs, is a goal that could be reached by allowing a high percentage of aircraft to execute profile descents to the runway. This would require procedures by which the pilot can be assured by ATC that when he finishes his descent the runway will be available to him. To plan runway use so precisely, the controller will need the ability to predict the position of every aircraft in the terminal area for thirty minutes or more into the future. With this knowledge, exact slot times for landing could be assigned. This is the essence of a 4-D ATC system. For the purpose of planning runway use, ATC does not really need to know where each aircraft is prior to its slot time, but for assuring separation, those data are vital. The controller must guarantee a conflict-free flight path to each aircraft in the approach and landing pattern.

Addressing the above issues will require a fair amount of real-time computer capability, but that will not be enough. Differences in equipment accuracy and pilot proficiency will mean that pilots will not always fly their assigned profiles precisely enough. There must be a feedback mechanism - probably the controller - that will monitor actual versus planned flight paths and mandate corrections for significant deviation. The controller must also manually accommodate aircraft that are not 4-D equipped.

It is conceivable that the problems of handling non-equipped aircraft might make it desirable to abandon the automated ATC system under some circumstances. Delays caused by heavy traffic may be so large that conflicts develop and slot times are missed. In that case it might be better simply to go back to first-come first-served, especially if the burden of fitting in non-equipped aircraft increases the controller's workload beyond what it otherwise would have been. This is shown in Figure 6-3. For moderate traffic levels, a 4-D system will produce fuel savings up to a point. At high traffic levels, minor deviations in slot times and flight paths cascade into bigger delays, eventually crossing the break-even line. Additional study and simulations will be required to determine the circumstances under which an automated ATC system based on 4-D navigation would be inferior to what now exists.

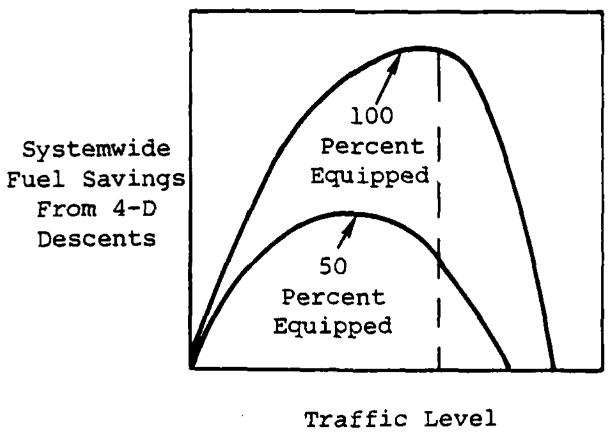

Figure 6-3. QUALITATIVE ASSESSMENT OF FUEL SAVINGS VERSUS TRAFFIC LEVEL AT VARIOUS PERCENTAGES OF AIRCRAFT EQUIPPED WITH 4-D CAPABILITY

CHAPTER SEVEN

CONCLUSIONS

7.1 BENEFITS OFFERED BY FLIGHT MANAGEMENT COMPUTERS TO AIRLINE OPERATIONS

The development of on-board flight management computers has been necessitated by the huge increases in jet fuel prices since 1972. Simultaneous reductions in the cost of computer hardware coupled with the increases in fuel prices reduced the payback period for an FMC to about one year for a wide-body aircraft in 1980. Ample economic incentives now exist for most airlines to equip all new aircraft and many existing aircraft with flight management computers.

The principal benefit offered by FMCs is the reduction of fuel consumption, cutting the cost of operations. There are also secondary benefits from reductions in crew workload. Table 7-1 shows many of the possible benefits an FMC can provide and quantifies the maximum savings over the handbook profile. Operating costs could also be reduced by relaxing certain routine ATC constraints. It is not the intent of this analysis to say that these constraints ought to be relaxed, only to quantify the cost reductions that could be made possible.

These benefits, as a percentage of total trip cost, do not vary markedly among the various turbofan and turbojet aircraft types. Therefore, a larger aircraft will show greater absolute fuel savings than a smaller one. However, the FMC cost will be about the same. Consequently, incentives to equip are greatest for the wide-body aircraft; virtually all of them should be equipped by the mid 1980s. For the mid-sized 727s, the decision to equip is based more on the remaining life of the equipment. Those aircraft scheduled to be retired in the 1980s will probably not be equipped; most others, including new ones, probably will be. For DC-9 and 737-sized aircraft, the payback period is longer than for 727s. There will be some retrofits in recently delivered, heavily used aircraft, but they will probably be a minority. A higher percentage of new aircraft will be equipped since a factory installation is cheaper. Cost incentives are probably inadequate to justify equipping business and commuter aircraft, although a smaller, less capable PDC could be developed that might be cost-effective for smaller aircraft. Further increases in fuel prices beyond the general inflation rate would further reduce the payback period and make an investment in an FMC more practical for smaller aircraft.

Table 7-1. FMC COST-SAVINGS TABLE

Flight Segment	Reference Section	Maximum Benefits Over Handbook (Percent)		Maximum Benefits From ATC (Percent)		Pilot Workload Benefits
		Short Segment	Long Segment	Short Segment	Long Segment	
Climb						
250 KIAS Limit	4.4	-	-	1.4	0.2	
Wind Compensation	4.5.3	0.1	<0.05	-	-	
Cruise						
RNAV Benefits	4.6.3	-	-	4.8	0.8	
Best Altitude	4.6.4	-	-	-	0.4	X
2,000-Foot Step Climbs	4.6.4	-	-	-	*	
Best Speed	4.6.4	0.1	0.6	-	-	X
Need to Step Climb	4.6.4	-	0.3	-	-	X
Wind Compensation	4.6.5	0.2	0.6	-	-	
Descent						
Top-of-Descent Point	5.3	2.9	0.2	-	-	X
Best Speed	5.2.4	1.3	0.3	-	-	X
Wind Compensation	5.2.5	0.4	0.1	-	-	
250 KIAS Limit	4.3	-	-	0.5	0.1	
Other						
Coupling Autothrottle and Autopilot	-	0.7	0.7	-	-	X
Best Hold Speed in Delays	5.4	0.4	0.1	-	-	
Totals	-	6.2	2.9	6.7	1.5	-

*Benefits are already included under "Best Altitude," which examines the impact of eliminating all altitude restrictions. If 2,000-foot vertical separation is required, the benefit is 0.3 percent over the current procedure.

A noneconomic benefit of FMCs is their ability to reduce pilot workload by presenting accurate, timely flight data to the crew. The FMC eliminates many tedious calculations and table inspections for performance limits, specific range, fuel consumption, fuel remaining, wind, wind compensation factors, and many other data. By automating many routine calculations not directly readable from engine instruments, crew time is freed for other duties. Autopilot and autothrottle systems, which may be driven by the FMC, relieve the crew of the burden of constantly maintaining proper altitude, airspeed, and throttle setting and thereby further reduce workload.

7.2 USE OF FMCs IN THE ATC ENVIRONMENT

The major use of an FMC is to select the flight profile that minimizes direct operating costs of the aircraft. Operating costs are dominated by fuel, but about 40 percent of costs are for time-related expenses such as crew salaries and scheduled maintenance. As a result, the minimum-cost flight profile is a compromise between minimizing trip time and trip fuel. It is generally about one or two percent less fuel-efficient and three to six percent faster than the minimum-fuel trajectory.

The primary variables affecting specific speeds and throttle settings in the profile are the aircraft type, takeoff weight, stage length, and wind and temperature conditions. Logistic factors such as on-time performance and curfews can influence an airline to attempt to make up as much time as possible on a flight and therefore change what profile will be flown. Knowledge of the above factors would allow a fairly precise estimate of the profile. Algorithms used to calculate the profile to be flown are different for each FMC manufacturer, and each will predict a different profile. However, the variances will be so subtle as to be insignificant to ATC.

Differences in profiles among various aircraft types are large enough to cause potential problems for ATC, particularly in terminal areas where a random mix of aircraft types, weights, and capabilities must be sequenced within limited airspace. However, the sensitivity of operating costs to descent speeds is so low that a band of speeds could be selected that would accommodate all aircraft within a small percentage of their best speed. However, frequent changes in throttle or prolonged use of speed brakes cost considerable fuel and should be avoided.

7.3 FUTURE DEVELOPMENTS EXPECTED

FMCs may be expected to benefit from current downward trends in hardware costs. More capabilities will be offered at roughly the same inflation-adjusted prices as today. Current experience with FMCs should result in future units designed with superior human engineering and display capability.

The FMCs will become progressively "smarter" as they are provided with interfaces with more and more of the other cockpit avionics systems. For example, the airlines may soon develop plans to tie in data links with their FMCs. Some thought has been given to linking an ACARS terminal with the FMC in order to provide real-time wind and temperature data, but this activity is still in the drawing-board stage. Whatever is ultimately done in this area, the FMC hardware is flexible enough and modular enough to accommodate almost any additional capabilities without major changes. All that would be needed would be an additional interface and the software to manipulate whatever data are needed. A data-link capability also has the potential to be exploited by ATC in conducting normal control duties and deserves further study on that basis.

Besides offering cost reduction and crew workload benefits to the airlines, FMCs offer other potential benefits to the air traffic control system as well. A 4-D navigation system would allow controllers to assign precise slot times to incoming aircraft. By meeting their assigned times, aircraft would, in effect, be sequencing and spacing themselves for landing. In the current terminal environment, aircraft are sequenced and spaced and delays are managed manually by the air traffic controllers. To automate this process and make 4-D based ATC a reality, a large number of factors must come together. First, ground computer capability would have to be upgraded substantially. Second, aircraft must be equipped with an FMC capable of meeting assigned slot times with sufficient accuracy. Third, procedures must be developed to accommodate unequipped aircraft, however infrequently. Fourth, a mechanism to handle unforecast wind problems must be developed. And finally, a wide assortment of technical, human factors, and administrative problems must be addressed. For these reasons, an operational 4-D system is unlikely to be seen in the 1980s, even though the necessary technology is for all practical purposes available now.

The percent of aircraft equipped with FMCs may well be high enough by the late 1980s to make such a system viable. It was estimated that at the busiest major hub airports, 70 to 85 percent of air carrier operations will be by FMC-equipped aircraft. The percentage will be highest for major coastal international airports, such as JFK and Miami, which will have the highest percentage of wide-body operations. Regional airports that accept small jet and feeder traffic from smaller cities will have a lower percentage.

Experience gained from using FMCs coupled with continuing improvements in electronics technology ensure a growing use of onboard computers in all phases of flight. FMCs will be routine equipment. Ultimately, they will have capabilities that will affect ATC's way of doing business as well.

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APPENDIX A

TABLE OF FMC CAPABILITIES

The production of flight management computers is dominated by a few avionics manufacturers. Reference 53, although slightly outdated, provides a good insight into product features and marketing strategies of the major FMC manufacturers.

Table A-1 shows a comparison of engineering design and capabilities of the major FMC products available today. ARMA, Delco, Lear Siegler, and Sperry are the major manufacturers of FMCs for the air carrier market. Simmonds Precision has a PDC in production but has not sold many units and appears to be dropping out of the market. Sundstrand abandoned its development work after installing prototype PDCs on a Flying Tiger 747 and an Alaska Airlines 727; therefore that system is not shown in the table. Safe Flight is the only manufacturer selling a simplified FMC for the small aircraft market; its product is a PDC designated for business jets and possibly commuters as well.

Table [illegible] FMC CAPABILITIES								
	Manufacturer							
[illegible]	ARMA	ARMA	Del[illegible]	Lear-Siegler	Lear-Siegler	Sperry	Simmonds	[illegible]
	Type of System							
	[illegible] FMS	FMS	PMS FMS	PDC PMS	FMS	FMS	PDC	[illegible]
[illegible]	--	[illegible]	747	727, 737	727, 737	757,767,A310	--	--
[illegible]	[illegible]	L-1011	747, [illegible]	727, 737	727, 737	--	727, [illegible]	Business Jets
Computer [illegible]								
[illegible] Memory	[illegible]K UV PROM + [illegible]K CMOS RAM	[illegible]K UV PROM + 16-32K core expandable to 128K	8K UV PROM + 16-24K RAM	32-64K UV PROM Up to 16K scratch pad RAM	32-64K UV PROM Up to 16K scratch pad RAM	16-32K RAM [illegible]	28K EPROM 4K scratch pad RAM [illegible] CMOS RAM	[illegible] ROM [illegible] RAM
Auxiliary [illegible] Storage	--	--	[illegible]K bubble	--	23[illegible]K optional loading unit	25[illegible]K words, reprogrammable from ground loader	--	--
[illegible] Instruction [illegible]	[illegible] sec	[illegible] sec	N.A.	[illegible]-4.[illegible] sec	[illegible]-4.[illegible] sec	[illegible]	--	N.A.
Computer Weight (Pounds)	45	45	N.A.	25	25	--	[illegible]8	[illegible]
Size	[illegible] ATR	1 ATR	--	1/2 ATR	1/2 ATR	1/2 ATR	[illegible]/4 ATR	[illegible]/4 ATR
Power Consumption (Watts)	[illegible]	[illegible]	--	100-150	100-150	[illegible]44	[illegible]	[illegible]
Control and Display Unit								
Type	Plasma gas discharge	CRT, CRT map	LED	CRT	CRT	CRT	7- and 16-segment incandescent	7-segment incandescent
Size (Inches)	4-1/2 x 5-3/4	5-3/4 x 9 and 8-1/4 x 9 (map display)	4-1/2 x 5-3/4	4-1/2 x 5-3/4	5-3/4 x 7-1/2 Ridges to prevent keystroke errors	5-3/4 x 9	3-3/4 x 5-3/4 and 3-1/4 x 3-1/4 (indicator unit)	[illegible]
Capacity	7 lines 15 characters/line	7 lines 15 characters/line	3 lines 24 characters/line	6 lines 13 characters/line	[illegible] lines 24 characters/line	13 lines 24 characters/line	[illegible] line - [illegible] characters and [illegible] indicator	[illegible] digits for airspeed, [illegible]
Character Type	5 x 7 dot matrix	5 x 7 dot matrix	5 x 7 dot matrix	5 x 7 dot matrix	5 x 7 dot matrix, [illegible] character sizes, black-on-white highlighting	Block letters [illegible] character sizes	[illegible]-segment	7-segment
Performance Options								
Minimum Cost (Standard)	Yes	Yes	Yes	Yes	Yes	--	Yes	No
Minimum Fuel	Yes	Yes	Yes	Yes	Yes	--	Yes	Yes
Handbook Profile (LRC)	Yes	Yes	Yes	Yes	Yes	--	No	Yes
Manual	Yes	Yes	Yes	Yes	Yes	--	Yes	No
Minimum Time	No	No	No	Yes	Yes	--	Yes	No
Maximum Endurance (Hold)	Yes	Yes	Yes	Yes	Yes	--	Yes	No
Engine-Out Handling	Yes	Yes	Yes	Yes	Yes	--	Yes	No
ARINC 702	No	No	Under Development	No	Yes	Yes	No	No
ACARS Interface Capability	No	No	Yes	Yes	Yes	Yes	No	No
4-D Software	No	Yes	--	--	--	--	No	No
Forecast Number of Installations by Aircraft Type (Optimistic, by 1995)								
DC-9/[illegible]	--			200		--	--	--
727	--		Not	300		--	[illegible]	--
DC-10	150-250		Available	120		--	--	--
L-1011	400-500		by	--		--	--	--
747	200-400		Aircraft	150		--	--	--
A300/A310	100-200		Type	--		[illegible]	--	--
757/767	--			--		1,600	--	--
Total	750-1,350		800-1,000	1,370		2,600	[illegible]00	No Air Carrier Aircraft
Fuel Savings Claimed	2-5% Mostly cruise, 1% in descent, little in climb		2% Depends on stage length	Minimum 3%; Typical 5%; Coupling adds 1%; VNAV adds 2%		No flight tests	2.64% TWA test Up to 5%	[illegible]
Hardware Cost	--		$75,000 + $60,000 training, maintenance	$100,000 to $250,000 including installation		$75,000 to $1[illegible],000 factory installation	--	$14,[illegible]

APPENDIX B

FUEL-BURN MODEL DESCRIPTION

Much of the analysis in Chapters Four and Five was based on a fuel-burn model currently being developed by the FAA Office of Environment and Energy (Reference 13). The model is an equation that yields the amount (in pounds) of fuel burned over a segment of flight as a function of aircraft constants, beginning and ending altitude, and beginning and ending speed. The equation balances thrust work with drag work plus the change in potential and kinetic energy. The equation is as follows:

$$\text{Fuel Burn} = \frac{\frac{K_1}{2}\bar{P}S_w D\bar{V}^2 + \frac{2K_2W^2D}{\bar{P}S_w\bar{V}^2} - \frac{W}{2g}(V_1{}^2 - V_2{}^2) - W(h_1 - h_2)}{K_3\bar{V}_e{}^{K_4\bar{V}} + K_5\bar{V}(h_1{}^2 + h_1h_2 + h_2{}^2) + K_6\bar{V}\,\frac{(h_1 + h_2)}{2} + K_7\bar{V}}$$

where: V_1 = beginning velocity (feet/second)

V_2 = ending velocity (feet/second)

$\bar{V} = \frac{V_1 + V_2}{2}$ = average velocity

h_1 = beginning altitude (feet)

h_2 = ending altitude (feet)

W = aircraft weight (pounds)

D = distance traveled (feet)

$\left.\begin{matrix} K_1 \\ \vdots \\ K_7 \\ S_w \end{matrix}\right\}$ = aircraft constants

$\bar{P}$ = atmospheric density (slugs/feet^3)

g = gravitational constant (= 32.2 feet/second^2)

This equation was used in an optimizing model to compute fuel burn between a series of short flight segments. The method is shown diagrammatically in Figure B-1. The total flight length, say 200 miles, is divided into several equal segments (6 in the diagram). The algorithm first calculates the fuel burn from point A to point G along the axis, at no change in

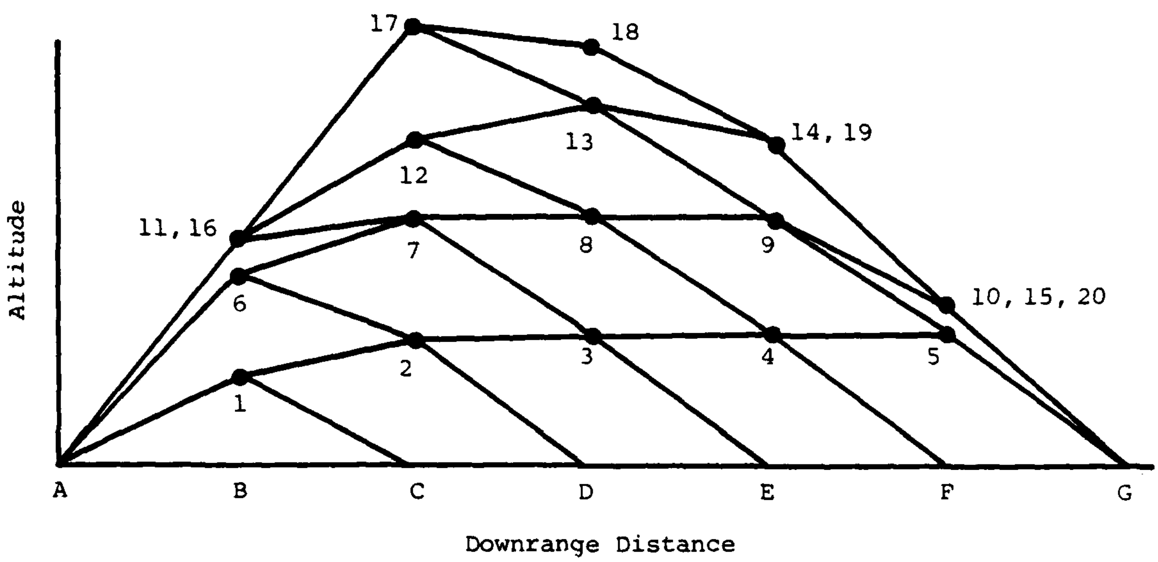

Figure B-1. COST/FUEL OPTIMIZATION ALGORITHM

altitude or speed. The model then iterates over altitude and speed combinations until it finds point 1: the combination which minimizes fuel consumption between A and C. The path C to G is unchanged, so there is a net improvement in fuel performance. (The diagram shows only altitude, but the algorithm iterates over both altitude and speed). The model then finds point 2, which minimizes fuel between point 1 and D, and similarly computes the other segments. After point 5 is computed, the algorithm starts again at the beginning - point 6 is found to minize fuel between point A and point 2. This process is repeated again and again with each change improving the overall fuel consumption, however slightly. Eventually, the point is reached where no further changes in the path result in fuel savings; the algorithm is finished and the optimum has been reached. Thus, the flight path is built from the ground up, always moving to higher altitudes and speeds. The range of altitudes and speeds permissible in a particular iteration is limited by the maximum engine thrust available. Figure B-2 shows a flow chart of the optimization method.

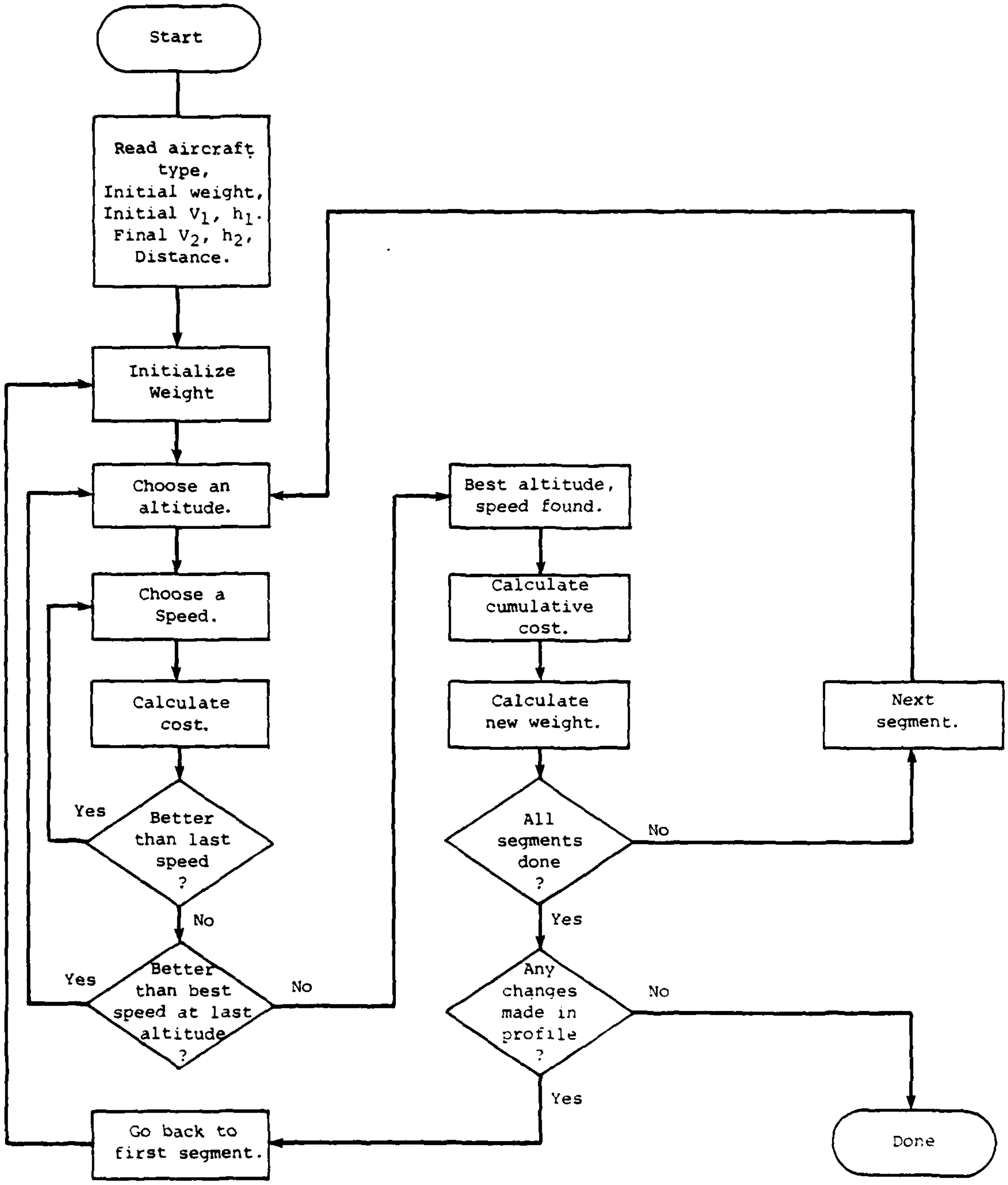

Figure B-2. OPTIMIZATION ALGORITHM FLOW CHART

This structure allows optimization not only for fuel costs alone, but also on a combination of fuel and time costs. Hourly costs of operation (excluding fuel) were obtained from Civil Aeronautics Board statistics derived directly from reports filed by the airlines. These reports are the source from which aircraft cost data published in *Aviation Week* and *Air Transport World* are compiled. Baseline fuel costs were taken as 85 cents per gallon, the approximate domestic price in the fall of 1980.

Figure B-3 shows the sample output table produced by the model. The profile shown is for a 300 nm trip in a 727-200, with a 40-knot tailwind. The results show the acceleration to 250 KIAS and the subsequent climbout at about 315 KIAS. The aircraft never quite reaches a cruise altitude, since the trip is so short; however, an actual flight plan for these conditions would include a cruise segment at 27,000 or 28,000 feet that would last about 30 miles or 4 minutes. When the model is run for flight segments of 500 nm or more, there is a definite cruise segment flown at 70 to 80 percent power and climbing 10 to 15 feet per minute as fuel weight is reduced. Descent is performed at idle thrust (about 10 percent power) and begun about 116 nm from the final approach fix. Without the tailwind it would have begun 100 to 105 nm from the final approach fix. The flight is assumed to begin and end at 2,000 feet altitude and 210 KIAS, presumably after flaps and gear are retracted on takeoff and before they are deployed for landing.

As can be seen from the figure, the model output provides data on altitude, speed, and pitch angle. Statistics are maintained on time of flight and fuel burn. The parameters for time and fuel cost can be modified to reflect any relationship between the two; if time cost is set to zero, the model will calculate a fuel-optimal path.

A problem with the model is that it does not account for the increase in drag due to operation at high mach numbers (greater than 0.8). As a result, it was not used for analysis of high altitude cruise performance. In the iteration process the mach speed was not permitted to go above the maximum long range cruise mach number for that aircraft (Table 4-1).

*** LIST OF LINKED FLIGHT SEGMENTS ***

AIRPLANE: B727 WEIGHTS: INITIAL=160000, FINAL=152911 LBS.

TIME COST = $ 825.00 PER HOUR FUEL COST = $ .85 PER GALLON

SCENARIO: 40 KT TAILWIND

SEG	---CLIMB,DESCENT---				------------	SPEEDS	-----------		DISTANCE(NMI)		TIME(MIN)		-------- FUEL	BURN --------			TOTAL COST ($)	
NO.	DEG	FPM	SPD	ALT	TAS	IAS	MACH	WIND	GRND	LEG	CUM	LEG	CUM	LBS	CUM LB	LB/HR	PCT MAX	LEG	CUM
				2000	210.0	203.9	.320												
1	1.8	868		2594	236.0	227.2	.360	40.0	276.0	6.2	6.2	1.3	1.3	470.3	470	21080	98.09	77.72	78
2	2.5	1257		4337	266.7	250.1	.409	40.0	306.7	6.9	13.1	1.3	2.7	462.0	932	20549	99.11	76.82	155
3	3.1	1694		6637	276.2	250.1	.427	40.0	316.2	7.2	20.2	1.4	4.1	442.3	1375	19450	99.71	74.53	229
4	2.4	1365		8511	284.2	250.0	.443	40.0	324.2	7.5	27.7	1.4	5.4	347.3	1722	15099	81.37	62.78	292
5	1.4	824		9634	318.3	275.1	.498	40.0	358.3	8.0	35.7	1.3	6.8	409.9	2132	18274	99.87	70.19	362
6	1.1	719		10618	369.9	314.8	.581	40.0	409.9	9.5	45.2	1.4	8.2	424.2	2556	18306	99.92	72.62	435
7	1.8	1352		12606	388.4	320.3	.615	40.0	428.4	11.1	56.3	1.5	9.7	452.7	3009	17510	99.89	78.41	513
8	1.9	1465		14826	397.4	316.2	.634	40.0	437.4	10.8	67.1	1.5	11.2	408.0	3417	16577	99.99	71.75	585
9	1.6	1261		16634	413.6	317.1	.660	40.0	450.6	10.4	77.5	1.4	12.6	368.4	3785	15903	99.94	65.58	650
10	1.5	1239		18388	420.2	315.2	.680	40.0	460.2	11.1	88.6	1.4	14.0	366.4	4152	15250	99.87	66.03	716
11	1.4	1135		19990	430.4	314.2	.700	40.0	470.4	10.8	99.4	1.4	15.4	338.8	4490	14732	99.98	61.69	778
12	1.4	1200		21650	435.0	308.7	.713	40.0	475.0	11.0	110.3	1.4	16.8	326.2	4816	14139	99.98	60.17	838
13	1.1	927		22852	445.8	309.9	.734	40.0	485.8	9.8	120.1	1.2	18.0	278.4	5095	13817	99.95	51.74	890
14	1.0	864		23930	455.4	310.8	.753	40.0	495.4	10.0	130.2	1.2	19.2	274.1	5369	13550	99.90	51.26	941
15	1.1	932		25016	460.8	308.4	.765	40.0	530.8	9.8	140.0	1.2	20.4	260.3	5629	13236	99.94	49.05	990
16	.5	827		25992	467.5	307.5	.779	40.0	507.5	10.0	150.0	1.2	21.6	255.8	5885	12993	99.93	48.49	1039
17	1.0	884		27098	471.2	303.8	.788	40.0	511.2	11.2	161.2	1.3	22.9	278.9	6164	12676	99.87	53.32	1092
18	1.4	1210		28708	456.6	286.0	.769	40.0	496.6	11.1	172.3	1.3	24.2	242.6	6407	10855	90.35	49.83	1141
19	-.1	-45		28643	422.4	264.9	.711	40.0	462.4	11.5	183.8	1.5	25.7	29.6	6436	1188	10.24	24.25	1165
20	-1.9	-1491		26453	391.7	255.5	.654	40.0	431.7	10.4	194.2	1.4	27.2	29.6	6466	1229	10.31	23.60	1189
21	-2.4	-1818		23770	380.3	260.1	.628	40.0	420.3	10.5	204.8	1.5	28.7	33.7	6500	1344	10.57	24.97	1214
22	-2.3	-1713		21183	366.5	262.2	.599	40.0	406.5	10.3	215.1	1.5	30.2	37.1	6537	1468	10.85	25.49	1240
23	-2.2	-1556		18928	350.9	260.9	.569	40.0	390.9	9.0	224.1	1.4	31.6	36.2	6573	1568	10.99	23.57	1263
24	-2.2	-1491		16846	336.9	259.3	.542	40.0	376.9	8.9	232.9	1.4	33.0	39.4	6612	1675	11.16	24.36	1287
25	-2.3	-1544		14551	328.7	262.7	.524	40.0	368.7	9.6	242.5	1.6	34.5	47.3	6659	1817	11.38	27.43	1315
26	-2.2	-1407		12397	315.9	251.4	.499	40.0	355.9	8.9	251.4	1.5	36.0	49.0	6708	1961	11.62	26.81	1342
27	-1.8	-1085		10718	293.1	249.0	.461	40.0	333.1	8.8	260.3	1.5	37.5	54.7	6763	2061	11.79	28.80	1370
28	-2.1	-1232		8761	284.5	249.3	.444	40.0	324.5	8.6	268.8	1.6	39.2	58.1	6821	2206	11.97	29.07	1400
29	-2.1	-1191	*	6873	276.7	249.6	.429	40.0	316.7	8.4	277.2	1.6	40.8	62.1	6883	2349	12.12	29.65	1429
30	-2.1	-1148	*	5056	269.2	249.7	.414	40.0	309.2	8.1	285.3	1.6	42.4	66.2	6950	2514	12.36	30.05	1459
31	-2.0	-1097		3349	261.9	249.2	.400	40.0	301.9	7.7	293.0	1.5	43.9	69.2	7019	2708	12.73	29.80	1489
32	-1.4	-705		2270	233.9	226.2	.356	40.0	273.9	7.0	300.0	1.5	45.4	70.0	7089	2747	12.68	29.82	1519

Figure B-3. SAMPLE MODEL OUTPUT

DATE
ILME