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Airline Energy Conservation Options

Summary Document

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7/27/73

Preface

In late May, 1973 the task of determining and evaluating measures for conserving fuel consumed by the airline industry was undertaken. This task was a part of the larger effort conducted by the Transportation Systems Center to determine measures that would conserve fuel in all transportation modes. This document identifies some fuel conserving measures applicable to airline operations and presents preliminary evaluations of the efficacy these measures.

Participating in the study were personnel from SIMAT, HELLIESEN & EICHNER, Inc. and Kentron Hawaii, Ltd. Their respective efforts appear as two separate reports. The concepts and numeric results of these studies are freely abstracted and referenced and form the bases for the conclusions in this summary document.

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1.0 Introduction

Background. The projected depletion of petroleum supplies toward the end of the century has forced an urgent and intense scrutiny of techniques and measures that would conserve fuel consumed in all transportation modes. The airline sector, expected to grow more rapidly than all other transportation modes, is the subject of this study of fuel conserving measures.

The objective of this study was to identify and assess fuel conserving measures that could be realistically applied to airline operations. The general criteria for measure selection and evaluation were:

- the measure would have a minimum impact upon the natural growth of air travel
- fuel conservation possibilities were at least one percent of total airline fuel consumption
- implementation, within constraints of costs, technology development, airline and public acceptance, could be realized within fifteen years
- realistic analytic methods and techniques could be applied to available data within the time allocated for the study to permit valid numeric conclusions.

The primary thrust of the study was to obtain a first estimate of the relative efficacy of the conservation measures with a view toward focusing the following study efforts.

Measures. Six fuel conservation measures applicable to airline operations were identified and assessed within the

the framework of this study.

Load Factors Increase
Delay Minimization
Cruise Speed Reduction
Direct Flight Paths
Flight at Optimum Altitude
Reduction of Ground Fuel Use

An amount of conserved fuel was estimated for each measure. Considerations other than fuel conservation were used in assessing each measure. These include; policies prerequisite to implementation; time scale for implementation; cost benefits; and public accommodation. In the study time scale it was possible only to frame these considerations for any succeeding detailed investigation.

The six measures do not represent an exhaustive list of possible fuel conserving measures. Other potential measures include: training flight reduction; maintenance of aerodynamically clean aircraft; reduction of fuel reserve requirements; etc. As a first approximation it was felt that these other measures would yield fuel savings of lesser magnitude, were difficult to implement, possible compromised safety, and/or were not amenable to reasonable quantification in the study time frame.

General aviation and military operations were not considered. General aviation currently consumes a small fraction of the fuel consumed by scheduled air carriers. Fuel conservation measures, short of a drastic nature, would have small impact upon total fuel conservation. Future growth projections for general aviation are, however, of significant enough proportions to warrant closer examination of future fuel use and conservation policies applicable to this aviation segment. Regulation of military operations in the interest of fuel consumption should be relatively straightforward and would have to be carried out in the different context of national security.

Contents of this Report. This document summarizes the fuel conserving possibilities of six measures applicable to airline operations and documented in references 1, 2, and 3. The succeeding section summarizes the findings of the study and is organized as to fuel conserving possibilities, implementation policy and schedule, and cost of implementation. The next section summarizes, in more detail, the investigation into each fuel conserving measure. The last section suggests the general directions of a further study effort.

The attached appendix contains some key assumptions and analyses used in this study. Also listed in the appendix are some of the study limitations and bounds imposed by the limited time available; in a measure, these bounds form the bases for the suggested further study efforts.

2.0 Summary

2.1 Fuel Conservation Concepts

Load Factor Increase: Increasing the number of passengers per flight will permit reduction in total aircraft miles flown while serving approximately the same demand. Reducing the number of flights will conserve fuel.

Delay Reduction: Terminal congestion results in fuel consuming delay. Reducing the delay will conserve fuel.

Cruise Speed Reduction: For given aircraft characteristics there exists a cruise speed at which minimum fuel is consumed. Aircraft tend to cruise at higher speeds; reducing the cruise speed will conserve fuel.

Direct Routing: The current flight-route structures requires, in general, a zig-zag or non-direct route to be flown between origin and destination. Direct routing would reduce the range between origin and destination. Range reduction implies less time-of-flight with a consequent fuel savings.

Optimum Altitude Cruise: For given aircraft characteristics there exists an altitude at which minimum fuel is consumed. Current air traffic control procedures restrict aircraft to altitude intervals. Reducing the altitude intervals and permitting optimum altitude bracketing would conserve fuel.

Ground Fuel Consumption: Currently aircraft use all available engines while taxiing over the airport surface. Turning off some engines during arrival taxiing would conserve fuel.

2.2 Current and Projected Conditions

In 1970 the air carrier fleet flew 135 billion passengers miles and consumed 8.9 billion gallons of fuel against a consumption of 113.2 billion gallons of fuel in all transportation modes.(4) The air carrier fuel consumption and the passenger miles are projected to grow at an annual 8.6% rate while all transportation fuel is projected at a 3.96% annual rate. Table 1 lists the projections for passenger miles and fuel consumption in selected years.

Table 1

Trends of Transportation

	1970	1974	1979	1990
Passenger Miles (Billions)	135	187.8	283.6	702.9
Air Carrier Fuel (Billions of gallons)	8.9	12.4	18.7	46.3
Transportation Fuel (Billions of gallons)	113.2	132.2	160.6	246.1

If no fuel conserving measures were instituted, then it is assumed that the six concepts over the selected years would be operative in the fashion indicated in Table 2a. These listed conditions may be at variance with current or projected operations; however they serve the purpose of a baseline against which the relative effectiveness of fuel conserving measures may be evaluated. The constancy of delay magnitudes through 1979, even with the recognized increases in operations, assumes that the effects of the upgraded third generation air traffic control system are introduced evenly over these years.

Table 2a

Baseline Conditions w/o Conservation Measure Implementation

	1970	1974	1979	1990
Load Factor	50%	50%	50%	50%
Delay (Minutes)	15,000,000	15,000,000	15,000,000	207,000,000
Cruise Speed (Mach No.)	.84	.84	.84	.84
Routing	Non-Direct		Direct	
Cruise Altitude	4000 Ft Intervals			
Ground Operations	All Engines On			

The fuel conserving measures are anticipated to result in the changed conditions listed in table 2b. The delay reduction measure is strongly sensitive to the number of operations which in turn is affected by the load factor increase. If 23,000,000 operations were projected for 1995, an increase of load factor to 75% would result in a reduction of the number of operations to about 15,000,000 operations. Thus increasing the load factor automatically results in delay reduction benefit.

2.3 Fuel Conservation

The amount of fuel that may be conserved by these measures is shown in table 3. Table 3 shows the fuel conservation possibilities where the impact of load factor increase has not been factored into the delay reduction measure. Thus one may evaluate institution of all measures where the load factor increase measure is excluded.

The load factor increase measure results in considerably more fuel conservation than the combination of all other measures (table 4). The fuel conservation possibilities are based on a 2% average passenger rejection rate and on the assumption that the standard deviation of demand may be reduced to 0.28 of the mean. If a 5% average rejection rate were tolerable in 1990, then the amount of fuel consumed would be about 24,000,000,000 gallons or 9.8% of the total transportation fuel.

The major detriments to implementing the load factor increase measures are: tendency to increase passenger rejection

Table 2b

Conditions with Conservation Measure Implementation

	1974	1979	1990
Load Factor	65%	70%	75%
Delay (minutes)			
(w/o Load Factor Effect)**	15,350,000	15,000,000	5,750,000
(w/Load Factor Effect)	7,470,000	6,570,000	15,000,000
Cruise Speed (Mach No.)	.82	.82	.82
Routing	-------------Direct----------		
Cruise Altitude	-----------2000 Ft Intervals---		
Ground Operation	----- 1 of 3, 2 of 4 engines off, arrivals ------		

*For computation purposes delay in 1995 used as delay in 1990

**Position/time scheduling assumed

Measure	1974 (1) Gallons	 (2) % of AF	 (3) % of TF	1979 Gallons	 % of AF	 % of TF	1990 Gallons	 % of AF	 % of TF
Load Factor Increase	3200	25.6	2.4	5740	30.7	3.6	16500	33.7	6.7
Delay Reduction w/ LF Inc	64	.52	.05	90	.5	.06	4500	9.8	1.8
Delay Reduction w/o LF Inc	--			--			4700	10	1.9
Speed Reduction	220	1.8	.17	340	1.8	.2	830	1.8	.34
Direct Routing	250	2.0	.19	370	2.0	.23	920	2.0	.37
Optimum Altitude	186	1.5	.14	280	1.5	.17	690	1.5	.28
Taxi Fuel Reduction	93	.75	.07	140	.75	.09	340	.75	.14

(1) All gallons in millions. (2) % of AF - % of Air Carrier Fuel (3) % of TF - % of fuel consumed in all transportation modes. (4) Delay data for 1979, 1990 assumed similar to 1984, 1995 respectively.

Actual $\frac{BTU}{\text{pass mile}} = 8500$

Fuel Conservation Possibilities

Table 3

Cruise $\frac{BTU}{PM} = 5000.$

	1974		1979		1990	
	Load Factor	Others	Load Factor	Others	Load Factor	Others
Gallons Conserved (Millions)	3260	749	5830	1130	21000	2980
Percent of Total Transportation Fuel	2.6	0.6	3.6	0.7	8.5	1.1

Relative Effectiveness of Load Factor Increase measure

Table 4

	1974	1979	1990
Gallons Conserved (Millions)	750	1130	7480
Percent of Total Transportation Fuel	0.6	0.7	3.0

Fuel Conserving Possibilities of All Measures Excluding Load Factor Increase

Table 5.

rate and distortion of the competitive aspects of the airline industry. If the load factor increase measure were not implemented, then the amount of fuel conserved by implementing all other measures would be as shown in table 5.

The fuel conserving values listed in tables for 1990 differ from those shown in table 4. This reflects the fact that a load factor increase reduces the number of operations and consequently the effect of delay upon fuel consumption. Table 5 assumes methods other than load factor increase are employed to reduce the effect of delay.

2.4 Implementation Policy and Schedule. Costs.

Three groups may be isolated as instrumental, in a primary groups sense, in determining and implementing policies necessary for institution of the fuel conserving measures. These groups, or sources of interest and concern, are: airline industry, government, and the public.

Costs. The desirability of instituting any measure will be directly affected by the cost benefit or disbenefit associated with the measure. Since all the measures reduce fuel consumption, then the airline industry will realize some savings due to reduced fuel usage. For some measures the airline industry would have to make outlays for additional equipment and crews which reduces the net cost benefit of the measure (Table 6).

Increasing the load factor should result in benefits beyond conserved fuel costs as a result of reduction in operating costs such as aircraft maintenance, number of flight crews, etc. The direct routing measure will require airline outlays for area navigation equipment purchase and maintenance which reduces the net cost benefit of this measure. Speed reduction would result in an increase in flight time costs that may offset the cost savings due to reduced fuel usage. The optimum altitude flight and taxi fuel reduction measures require no airline industry outlays and approximately the total conserved fuel costs are realized as a net benefit.

The reduction of aircraft delay via institution of the load factor increase measure results in a further cost benefit for the airline industry. The magnitude of delay cost disbenefits projected into the 1990 time frame are significant. Reducing this delay via institution of a delay reduction measure would result in a cost benefit in excess of

Measure	Disbenefit	Benefit	Net	Government Cost**	Comment
Load Factor Increase	------	450*	450	(1)	
Delay*** Reduction	------	16	16	(1)	In 1990-1995 era net benefit in 1973 dollars is $1,100,000,000
Speed Reduction	21	21	---	(1)	
Direct Routing	20	42	21	(3)	
Optimum Altitude	----	18	18	(2)	
Taxi Fuel Reduction	---	9	9	(2)	

* All numbers are relatively weighted. May be assumed as millions of dollars

** Government Cost scale ranges from costs associated with regulatory and monitoring personnel (1) to full scale government development, installation programs (5).

*** Computed @ $6.00/min

Trends of Airline Cost Benefits - 1974

Table 6

$1,000,000,000. in the 1990 time frame. (Table 6)

For each of the measures there would be some outlay of government dollars. For the load factor increase, delay reduction via load factor increase, and the speed reduction measures, the government costs would be those necessary to support government personnel involved in establishing and monitoring policy. For the optimum altitude and taxi fuel reduction measures the government costs would increase to include training of air traffic control (ATC) personnel and possible addition to the ATC force. The direct routing measure would require formal government programs to devise, test, and implement an ATC system using area navigation equipment. If the load factor increase measure is not implemented, then an extensive government program would be required to insure delay reduction in the 1990 time frame. The costs associated with this program would be typical of those associated with major FAA programs.

Table 6 summarizes the costs benefits. The airline cost data was culled from CAB airline financial reports and no exhaustive financial analysis was conducted. The cost numbers are presented as a first order approximation and serve only to be indicative of cost trends. No cost values are assigned to government programs or to passenger benefits; these cost benefits will be analyzed in a further study.

Airline Agreement. The airline industry, it may safely be assumed, will very likely agree to implement those measures that result in profit increase (table 7). The likelihood of implementation by the airlines will increase in direct proportion to the profit increase. Thus, institution of the load factor increase measure, with a consequent large profit enhancement, would very likely be agreed upon by the airline industry. The cruise speed reduction measure may not result in a net cost benefit to the airline industry; thus the airline industry may not be too

Measure	Airline Agreement		Government Action	Public Accommodation (1)		Initial Implementation Date
	Likelihood	Type		Type	Intensity	
Load Factor Increase	Very likely	Multilateral	Monitor	(d) Some Passengers Rejected (b) Noise, Pollution Abatement	Potentially Severe High Benefit	1974
Delay Reduction (2)	N/A	N/A	Monitor	(b) Passenger Delay Reduction	Mild	1974
Cruise Speed Reduction	Questionable	Unilateral	Regulation	(d) Passenger Delay Increase	Negligible	1974
Direct Routing	Likely	Unilateral	Government Program	(b) Passenger Delay Reduction	Negligible	1979
Optimum Altitude Cruise	Likely	Unilateral	Government Program	----------	--------	1975
Taxi Fuel Reduction	Likely	Unilateral	Monitor	----------	--------	1974

(1) (d) = disbenefit, (b) = benefit (2) Includes effect of Load Factor Increase

Airline Fuel Conservation Measures:
Implementation Alternatives and Schedule

Table 7

eager to agree to implementation of this measure.

These measures would in all probability be unilaterally implemented by individual air carriers unless such implementation results in deterioration of a competitive posture. The load factor increase measure is a potential instance of the latter type of measure. Where this occurs, then multilateral agreements supervised by the airline industry with monitoring would have to be initiated.

Government Role. The government role will extend from the relatively passive one of monitoring airline agreements to full scale research, development, and test programs. For classification purposes the roles may be described as:

- Monitoring - encouraging and monitoring airline agreements.
- Regulation - establishing regulatory policy, altering tax and fare structures, maintaining public safeguards, policing and enforcing penalties.
- Government Program - instituting research, development, and test programs; supply of ATC personnel to operate and maintain facilities.

It is anticipated that the government will act in a monitoring role for the load factor increase and taxi fuel reduction measures while the cruise speed reduction measure would require government regulation (table 7). The direct routing and optimum altitude cruise measures would require government programs. If the load factor increase measure is not implemented, then an extensive government program would be required to reduce delay significantly.

Public Accommodation. The public is affected in at least three ways: inability to obtain seats, time of flight effects, and community disaccommodation.

Increasing the load factor increases the probability that a certain percent of the public desiring to fly will not be able to obtain seats at a desired time (c.f. sec. 3.1).

Those measures that alter nominal flight times result in benefiting or disbenefiting the passenger. Two of the measures - delay reduction and direct routing - decrease time and result in a passenger benefit while the speed reduction measure increases passenger time with a resulting passenger disbenefit. However, the amount of time increase or reduction per passenger is relatively small and in all probability is neither a benefit nor disbenefit.

Increasing load factor will reduce air pollution and noise in proportion to the decrease in flight operations. The reduction in operations will mitigate the press for elaborate airport construction and expansion with a consequent trend to local community benefit.

Table 7 summarizes the policy implementation considerations.

Schedule. All of the measures with the possible exception of the direct routing measure could be implemented by 1975. The planning and equipping of aircraft to realize the direct routing measure is currently underway and could be realized by 1979. If the load factor increase measure is not implemented, then the time period for implementing a significant delay reduction measure could be in the late 1980's.

3.0 Measures Discussion

3.1 Load Factor Increase

Concept

The air carrier fleet, accounting for over 86% of the fuel consumed by civilian aircraft, operates at less than full capacity. Currently, on an national average, about one half of the seats flown are occupied by passengers i.e., the average load factor is about fifty percent (50%). If a number of flights were eliminated, then, assuming the same amount of passengers desiring to fly, the occupancy rate or load factor would rise. Eliminating a number of flights would conserve fuel.

Elimination of flights would tend to increase the number of passengers who will not obtain seats, i.e., the rejection rate will increase. Thus, selection of load factor must be balanced by considerations of feasible rejection rates.

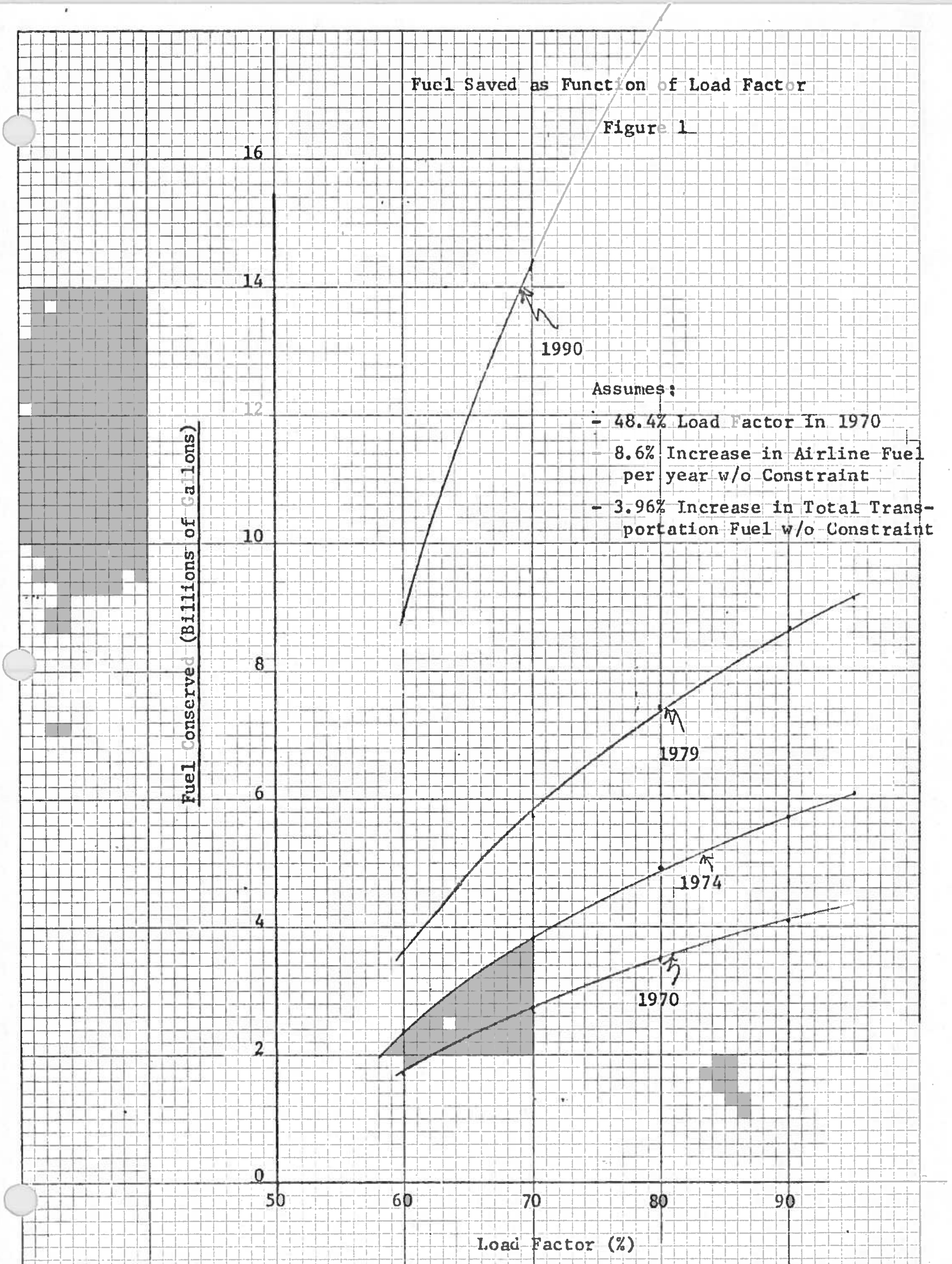
Fuel Consumption and Conservation

The fuel conserving effect of the load factor increase measure can be quite significant. If the load factor could be increased to about 90%, then as much as 8.5% of the total transportation fuel, or 21 billion gallons, would be conserved in 1990.

The fuel conserving effect of the load factor increase measure becomes more pronounced as the demand for air travel increases. As an example, for an increase in load factor from 60% to 70% the fuel savings will increase by 5.5 billion gallons in 1974 and by 1.4 billion gallons in 1974 (figure 1). An appropriate strategy would, therefore, increase the load factor as the demand increases to realize fuel conservation as fuel supplies tend toward depletion. Figure 1 shows the possible fuel savings as the load factor increases in selected years and figure 2 shows this fuel conservation as a ratio to total transportation fuel consumption.

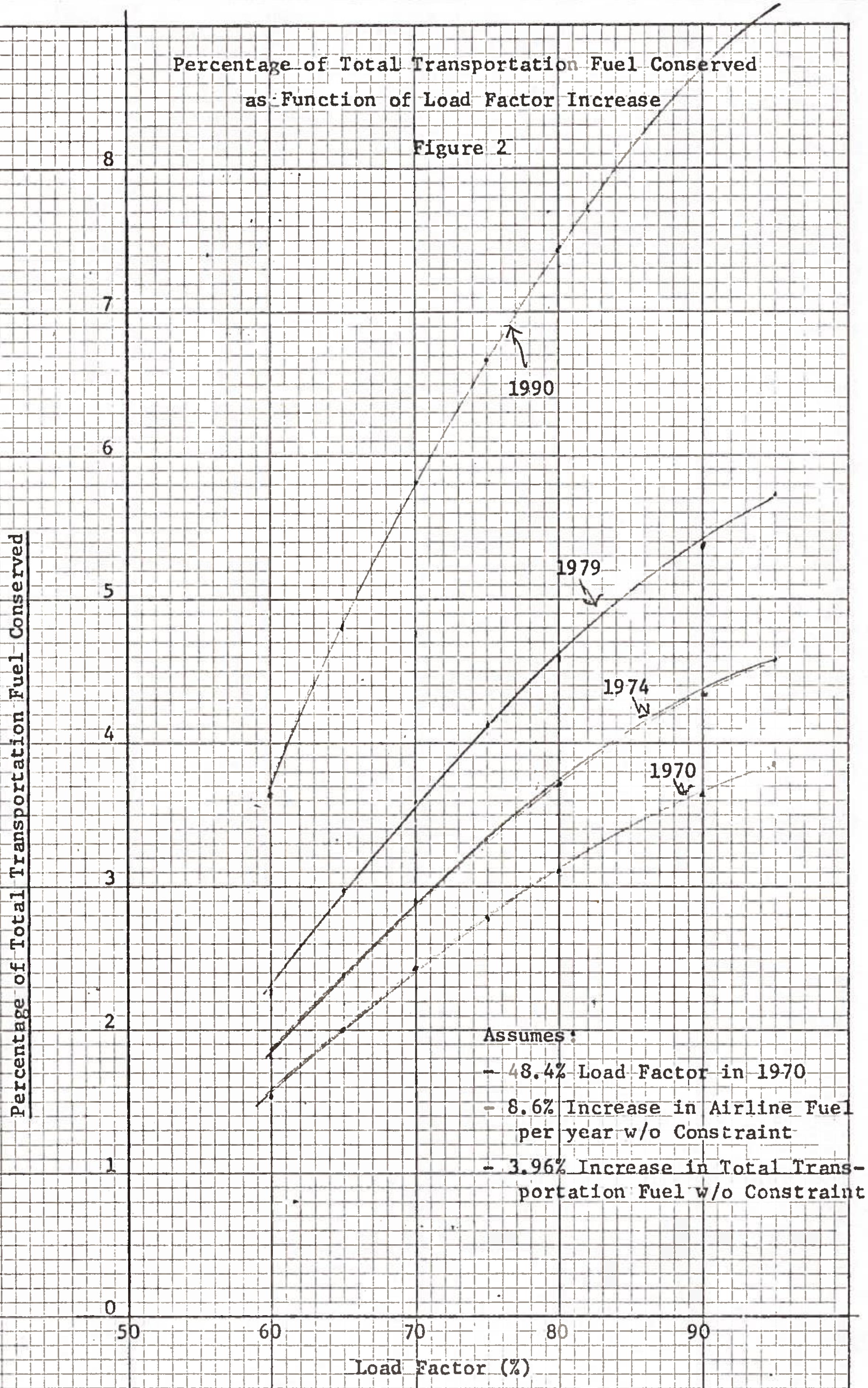
Fuel Saved as Function of Load Factor

Figure 1



Assumes:

- 48.4% Load Factor In 1970
- 8.6% Increase in Airline Fuel per year w/o Constraint
- 3.96% Increase in Total Transportation Fuel w/o Constraint



Percentage of Total Transportation Fuel Conserved as Function of Load Factor Increase

Figure 2

A limiting factor to increasing the load factor is the tendency to increase the passenger rejection rate. The demand, or the number of people desiring to fly, would have a probability characteristic. Assuming this demand to be characterized by a normal probability density function with mean, m, and a standard deviation, σ, then the rejection rates will be as plotted in Figure 3.

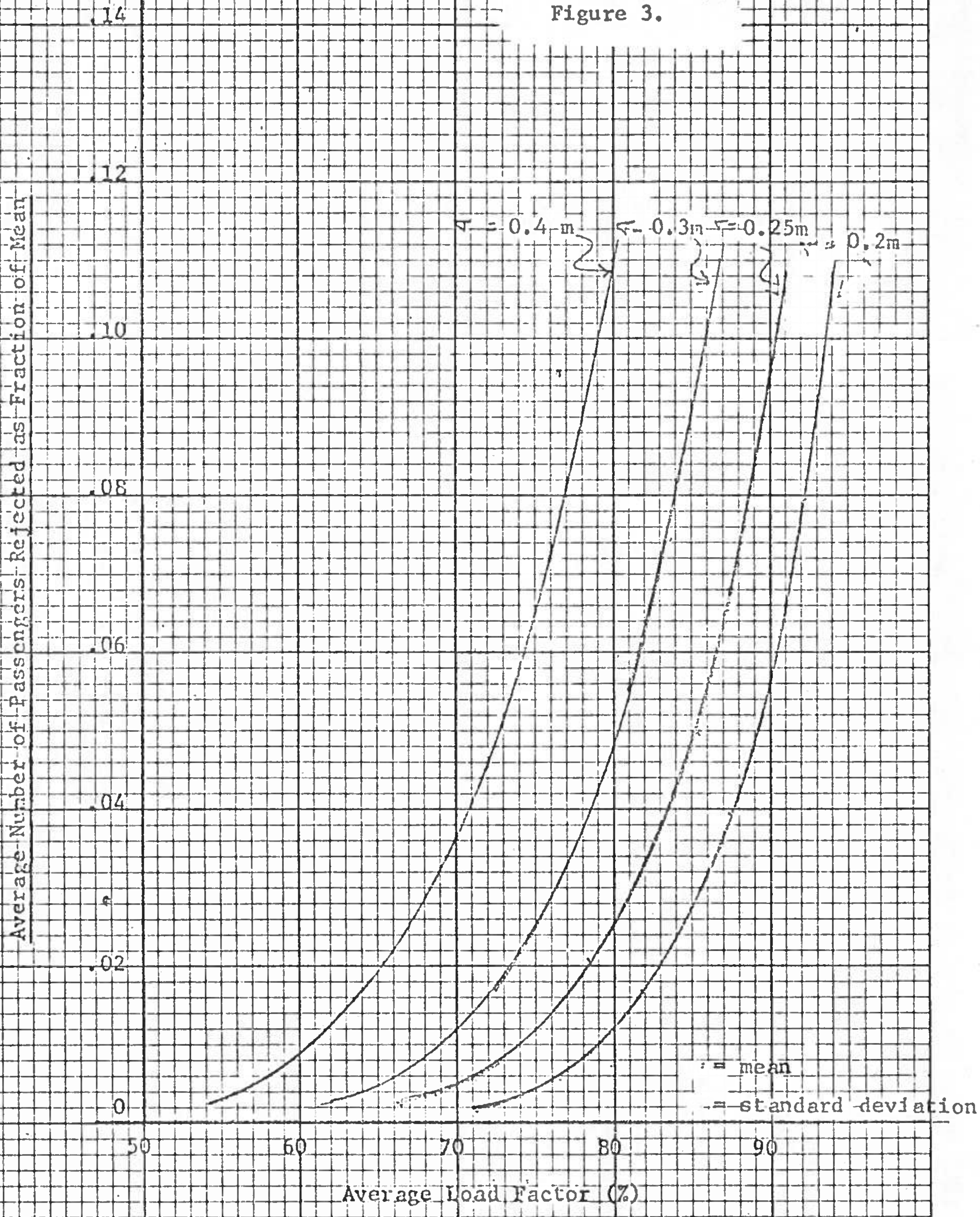
If a 2% average rejection rate is permissible, then about a 65% load factor may be realized if the demand distribution were characterized by $\sigma = 0.4$ of the mean. The standard deviation is determined by behavior of air travelers. It is possible to modify traveler behavior by fare incentives, educational campaigns, etc., so as to reduce the standard deviation of the demand. Thus, it would appear feasible to increase the load factor by some percentage points without raising the rejection rate. Table 8 lists some possible standard deviation reductions and the resulting load factor increases. If a 2% average rejection rate is tolerable, then the fuel savings of table 8a may be assumed to be appropriate conservation levels.

Implementation Policy and Schedule

Markets with jet frequencies of 3/day or more account for more than 50% of the fuel consumed by domestic air carriers. In these markets the air carriers would be encouraged to unilaterally alter schedules to realize the higher load factors. Where these unilateral moves, if not simultaneously carried out by all carriers, operate to the detriment of a carrier, then multilateral agreements would be encouraged. In the event that the carriers cannot agree, a joint DOT, CAB committee would determine a flight reduction policy for the carriers. No matter how the agreement is reached in these markets the affected

Rejection as a Function of Load Factor

Figure 3.



Year	Standard Deviation	Load Factor	Percent of Total Transportation Fuel Conserved
1974	0.4 m	65%	2.4
1979	0.35m	70%	3.6
1990	0.28m	75%	6.7

(@ 2% Rejection Rate on the Average)

Possible Airline Fuel Conservation

Table 8a

Year	Standard Deviation	Load Factor	Percent of Total Transportation Fuel Conserved
1974	0.4 m	73%	3.1
1979	0.33m	78%	4.5
1990	0.27m	83%	7.9

(@ 5% Rejection Rate on the Average)

Possible Airline Fuel Conservation

Table 8b

carriers will not be permitted to transfer the excess capacity generated into the low frequency markets.

Reducing the number of flights in low frequency markets - two/day or less - would, in a number of cases, seriously disaccommodate the public in these markets. Two possible approaches to increasing the load factor in these markets would be: alteration of aircraft type serving these markets and linking of these markets in a multistop network.

The initial approach to low frequency markets would freeze the capacity in these markets until a fuel conservation policy could be established. On a national, statistical basis a 65% load factor would be reached in 1974 where the 1970 load factor is 50% and the demand for air travel grows at a rate of 8.6% per year. Thus, it would appear that the load factors in table 8a for the national air carrier fleet could be realized in the indicated years.

If first class seats are removed, it is possible to obtain a 4.5% increase in seating capacity without increasing the number of flights. This tactic, first class seat removal, may be used as a buffer to the incremental batch nature of airline production increases. That is, an increasing demand may be met, to an extent, by first class seat removal while maintaining the same load factor.

<u>Costs</u>

<u>Disbenefits</u>. These disbenefits could be principally realized in:

(1) Increase in passenger travel in off hours with consequent increase in passenger expense

(2) Non-recurring costs associated with airline scheduling activity

Benefits. These benefits could be principally realized by the airline industry in the net reduction of flying operations (table 9).

Approximate impact of 15% reduction in truck airline activity ($ in millions): Table 9

	Year Ended* 9/30/72	Adjusted for Capacity Reduction
Revenues	$ 7,329	$ 7,329
Flying Operations	(3,031)	(2,576)
General & Administrative	(3,183)	(3,183)
Depreciation & Amortization	(697)	(697)
Operating Profit	417	873
Non-Operating Expenses	(156)	(156)
Profit Before Taxes	261	717

*CAB, Air Carrier Financial Statistics for Year Ending 9/30/73

Barriers to Implementation

- The public will be disaccommodated to the extent that the rejection rate is intolerable.
- A major competitive instrument within the airline industry will be modified and regulated.
- Adverse impact upon employment within the airline and aerospace industry.

3.2 Delay Reduction

Concept

When the number of operations at an airport approach the capacity of the airport system, then individual aircraft will be delayed. This delay may take the form of holding patterns for the arrivals and a queue of departing aircraft at the runway threshold. During the delay, the engines are consuming fuel. If the amount of delay could be reduced, then a proportionate amount of fuel would be conserved.

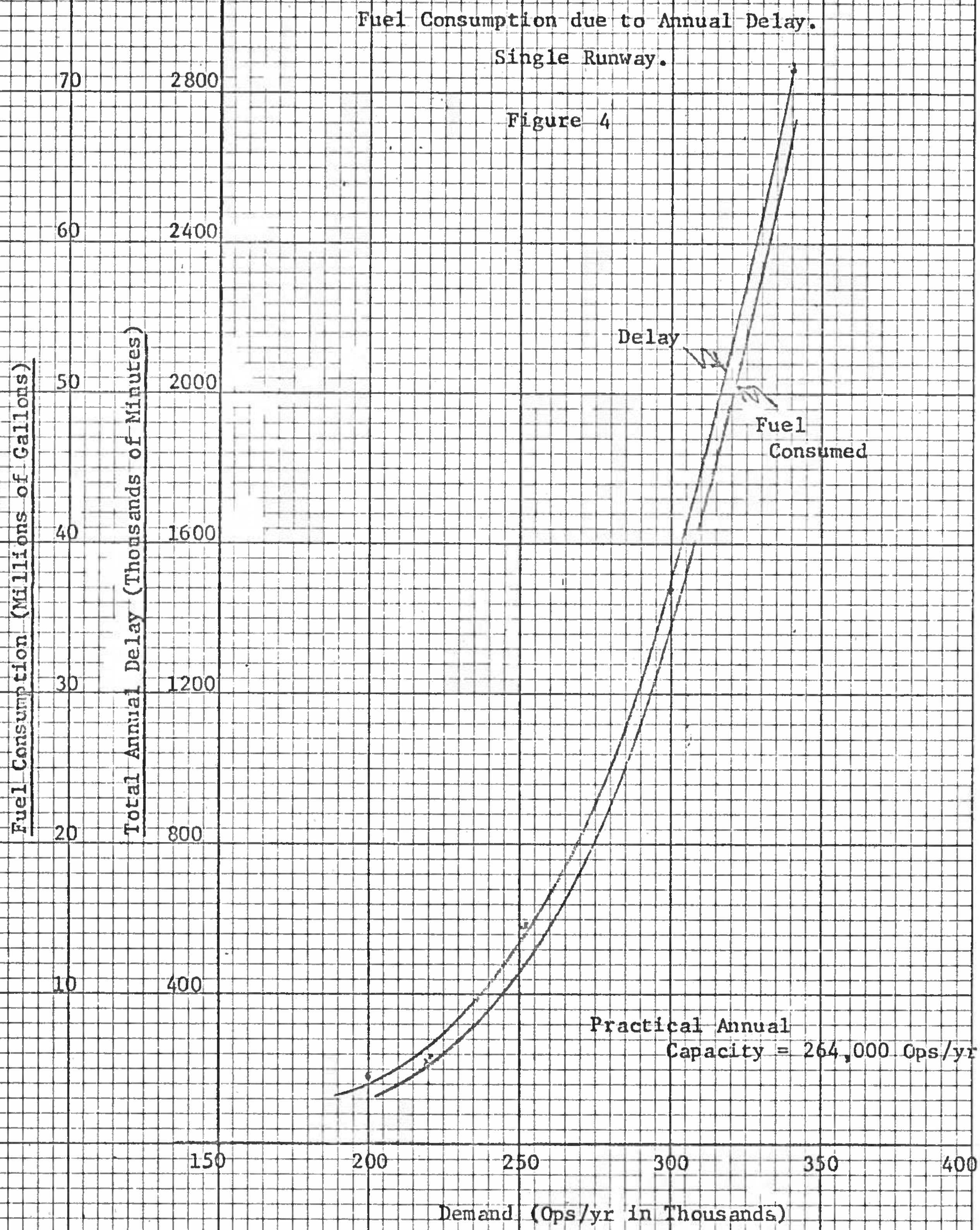
Fuel Consumption and Conservation

The average delay, and consequently fuel consumption is magnified as the operations increase at an airport with a given capacity (fig. 4). By projecting from current and predicted levels of demand and capacity at 23 major hubs it is possible to predict the national air carrier fuel consumption due to delay. Table 10, which depicts this, incorporates the capacity increase in 1984 when the upgraded third generation air traffic control system (U3GATC) will be implemented.

Reduction of delay can be accomplished by:

1. Increasing the capacity of the national airport system
2. Reducing the demand or number of operations
3. Imposing a firm position/time scheduling upon the aircraft.

The capacity of the national airport system can be increased by improvements in air traffic control and/or addition of runway systems. The U3GATC is and will be an improved air



Fuel Consumption due to Annual Delay.

Single Runway.

Figure 4

	1971	1984*	1995*
Demand (Operations/year)	9,713,000	15,333,000	23,000,000
Annual Delay (Minutes)	15,350,000	15,026,000	207,000,000
Fuel Consumption (Gallons)	364,000,000	357,000,000	4,905,000,000

* Upgraded Third Generation Air Traffic Control System Implemented

Fuel Consumption Due to Air Carrier Delay

Table 10

traffic control system. Programs of this magnitude are costly and can require a cycle of study, development, test, and implementation of more than ten years. If improvements upon U3GATC are projected for 1995, that (1) reduces the arrival separation to 2nm; (2) decreases the interarrival time inaccuracy to 5 seconds; and, (3) extends the level of automation, then it is possible to realize a reduction in fuel consumption due to delay from 4,905,000,000 to 2,580,000,000 gallons.

Improving the national runway system requires overcoming strong community and environmental objections and is faced with real estate limitations. Some improvements are contemplated and should be realized by 1984. The effects of possible runway improvements and the U3GATC system are reflected in table 10.

Reducing the number of operations would reduce the demand and consequently the delay. An effective method for reducing the number of operations is to increase the load factor as discussed in section 3.1. The resulting reduction in delay and fuel consumption is shown in table 11.

Imposing a firm position/time scheduling upon all aircraft using the system would result in average delay reductions to the arrival and departure time uncertainties. Assuming implementation by 1995 and further assuming the three sigma value of 15 seconds then the fuel consumption would be of the magnitude shown in table 12. The possible reduction in 1995 as a result of implementing U3GATC, load factor increase, and position time control are summarized in table 13.

Table 11

Effect of Load Factor Increase on Fuel Consumption Due To Delay

	1971	1984[2]	1995[2]
Load Factor[1] Percentage	65%	70%	75%
Demand (Operations/Yr)	7,470,000	10,950,000	15,320,000
Annual Delay (Minutes)	7,470,000	6,570,000	15,000,000
Fuel Consumed by Delay (Gallons)	177,000,000	155,709,000	356,000,000

[1] Current Load Factor Assumed at 50%

[2] U3GATC and Improved Runways

Table 12

Fuel Consumption Due to Air Carrier Delay

	1971	1984[1]	1995[1,2]
Demand (Ops/Yr)	9,713,000	15,333,000	23,000,000
Annual Delay (minutes)	15,350,000	15,026,000	5,750,000
Fuel Consumption (Gallons)	364,000,000	357,000,000	136,000,000

[1] Upgraded Third Generation Air Traffic Control System Implemented

[2] Position/Time Scheduling Implemented

Table 13

Possible Delay Fuel Consumption in 1995

Events Implemented	Delay Fuel Consumed
U3GATC	4,905,000,000
U3GATC and 75% Load Factor	356,000,000
U3GATC and Position/Time Scheduling	136,000,000
U3GATC, 75% Load Factor, and Position/Time Scheduling	91,000,000

Implementation Policy and Schedule

A feasible program for reducing delay would consist of the events and associated scheduling shown in table 14. The following comments apply to the events of table 14:

- Implementing load factor increases would require the agreements and regulations discussed in Section 3.1.

- The U3GATC system is currently under development and installation and no further policy action is required.

- Implementing a firm position/time scheduling requires establishing a DOT-FAA program. The program would be similar in nature to other FAA programs and would require exercising standard FAA procedures to establish the program. The program could be adapted to such current programs as Airport Ground Traffic Control, Advanced Air Traffic Management, Area Navigation, ARTS, Central Flow Control, etc.

- Implementing improved or new runways in the form of airport expansion or new airport construction would require federal assistance to local and regional authorities. This assistance might be rendered not only through the current grants program but also through legislation that would minimize community override capability. Operating rules and guidelines would have to be agreed upon between DOT and EPA.

Costs

Disbenefits. Since the U3GATC system and runway improvements are currently being developed, they are not a cost disbenefit resulting from delay reduction.

Table 14

Implementation Schedule

Event	Schedule
Implement 65% Load Factor	1974
Implement U3GATC	1984
Improve Runways (Currently under development)	
Implement 70% Load Factor	1984
Implement Firm Scheduling and 75% Load Factor	1995

Increasing the load factor results in disbenefits as increase in passenger expense and the costs for airline rescheduling (Section 3.1).

The costs of implementing a firm position/time scheduling will be borne by the airline operator and the FAA. Assuming area navigation or similar equipment and a relatively high level of automation onboard the aircraft in 1995, then a relatively inexpensive onboard addition should permit position/time implementation. For the FAA, with extensive ground computation facilities existing by 1995, the major costs should be the non-recurring costs associated with software development.

Benefits. The major costs benefits will be reaped by the airline operator as the average delay is decreased. For the airline operator, assuming a cost of $6/minute for flying operations, the cost savings will be as listed in table 15. The additional savings to the airlines in reduced manpower and equipment are not shown.

Barriers to Implementation

- Outlay of costs for government programs.
- Barriers applicable to Load Factor increase.

Year	Event	Cost of Delay	Year	Event	Cost of Delay
1971	-----	$90,000,000	1971	-----	$90,000,000
			1974	Implement 65% Load Factor Increase	$45,000,000
1984	Implement U3GATC & Improved Runways	$90,000,000	1984	Implement U3GATC & Improved Runways	$39,000,000
				Implement 70% Load Factor	
1995		$1,240,000,000	1995	Implement 75% Load Factor	$23,000,000
				Implement Position/ Time Scheduling	

Cost Disbenefits Resulting from Delay

Table 15

3.3 Cruise Speed Reduction

Concept

Aircraft cruise at speeds which are compromises between aircraft flight and handling characteristics and aircraft operating costs. The nominal cruise speeds are set above the minimum fuel consumption speed (fig. 5). Fuel would be conserved by reducing the cruise speed to a point closer to the minimum fuel consumption point.

Fuel Consumption and Conservation

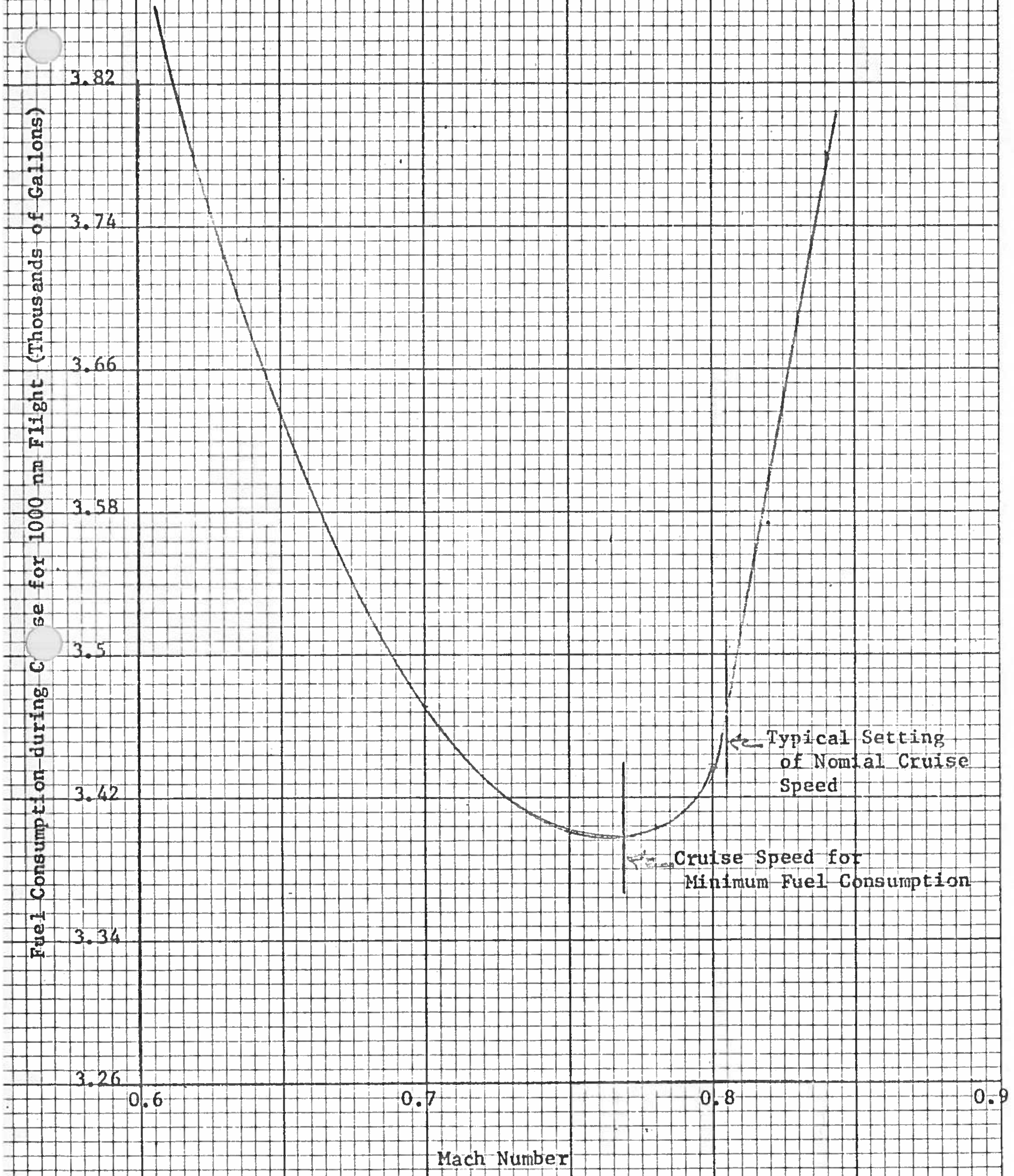
The change in fuel consumption as speed is varied is a function of aircraft type, gross weight, and altitude of operation. Fig. 6 shows the percentage reduction in fuel consumption for three different aircraft types at various gross weights. For a speed reduction of 0.02 Mach, approximately 1.8% of the total fuel consumed by air carriers would be conserved (table 16). At a speed reduction of 0.04 Mach, a fuel savings of about 2.2% is realized.

Implementation Policy and Schedule

The measure could be implemented by the air carriers on a unilateral basis. Since the desire to fly at higher speeds is dictated by the relative costs of fuel to other flying expenses, then an increase in fuel tax might be implemented if the airlines do not agree.

Costs

Disbenefits. As the speed is reduced the time of flight

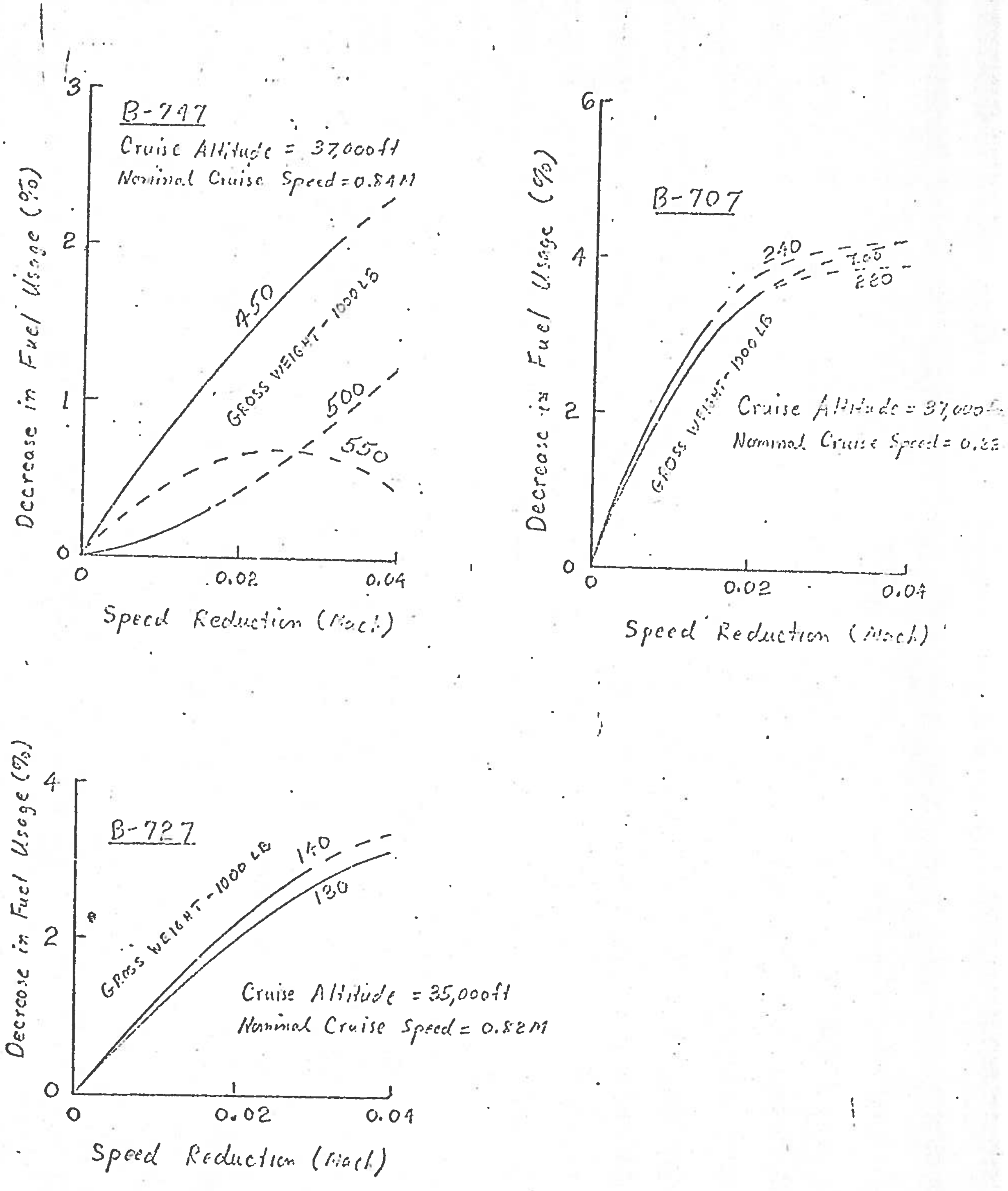


Typical Setting of Nomial Cruise Speed

Cruise Speed for Minimum Fuel Consumption

Typical Fuel Consumption inCruise

Figure



Fuel Useage vs. Speed

Figure 6

TABLE 16 ANNUAL SAVINGS FOR TURBOFAN OPERATION/ PASSENGER AND CARGO

	ANNUAL FUEL USAGE (1)			ESTIMATED ANNUAL FUEL SAVINGS			
				0.02 Mach Reduction		0.04 Mach Reduction	
	All Operations (Million Gal.)	AirBorne Operations (Million Gal)	Cruise Operations (Million Gal)	Rate	Total (Million Gal)	Rate	Total (Million Gal)
4-engine Wide Body	8.12	789	710 (90%)**	0.8%	5.7	1.2%	8.5
4-Engine* Reg. Body	37.15	3570	2860 (80%)**	3.6%	102.8	4.0%	114.2
3-Engine Reg. Body	24.40	2193	1320 (60%)**	2.0%	26.3	3.2%	42.1
2-Engine	13.09	1222	610 (50%)**	2.0% ***	12.2	3.0% ***	18.3
Total	82.76	7774	5550	XXX	147	XXX	183

* Includes Turbo-jet hours, since these are significant
** Estimated Percentage of Cruise hours to Total Airborne Time
***Estimated to be similar to 3-engine jets
(1) CAB Operating Cost Report, August 1972 (Figures are for 1971 and include all domestic operations plus one-half of International Operations)

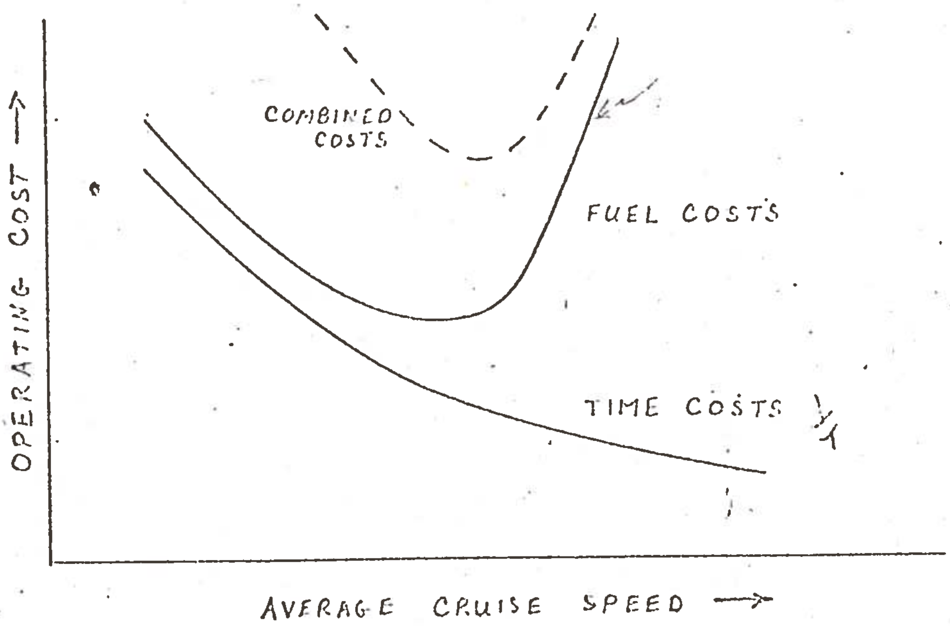
is increased and consequently the flight operations cost is increased. For a given aircraft, the cruise speed is a compromise of the costs between fuel and other flying costs (fig. 7). Thus, where the current cruise speed is set at a minimum, then a speed reduction will increase the costs.

Increasing flight times will require the airlines to add more flight crews. Some non-recurring costs will result from the necessary rescheduling.

Benefits. Savings in fuel costs to airline industry

Barrier to Implementation

- Increased operating costs to airlines



Cost vs Speed

Figure 7

3.4 Direct Routing

Concepts

Aircraft of the air carrier fleet generally navigate along prescribed directions to ground based radio navigation stations, i.e. VOR stations. The siting of these stations are such that an aircraft may fly a zig-zag or non-direct route from origin to destination. If the flights paths could be made direct, then the distance traveled would be shortened between origin and destination with a consequent fuel saving.

A feasible technique currently receiving considerable attention employs the concept of area navigation. In this concept an onboard sensing and computation system operates upon radio signals from ground based systems to compute such parameters as current aircraft position. Further onboard computations permit the aircraft to navigate along a direct route.

Fuel Consumption and Conservation

Examination of the route structures between a number city pairs shows about an average of 2% range reduction from current non-direct routing to direct routing (Table 17).

Implementation Policy and Schedule

The concept and useage of area navigation has been studied for some years and a number of active efforts are underway. Participating in these study, development, and test efforts are the FAA, DOT, the airline industry, equipment manufacturers, and aircraft manufacturers. The central problems in implementing this concept are:

Table 17 Distance Reduction

Distance class 0-400 NM

City Pair	Non-Stops/Day	By Jet Route	Direct	% Reduction
SF→LA	130	290 NM	290	~ 0
WASH→BOS	31	370 NM	340	8.0

(Weighted) Average % = 1.5%

Distance class 400-800 NM

City Pair	Non-Stops/Day	By Jet Route	Direct	% Reduction
ATL→WASH	24	485 NM	472	2.7
CHI→ATL	17	543 NM	530	2.3
WASH→CHI	32	559 NM	540	3.5
SEATTLE→SF	17	597 NM	578	3.2
ATL→DAL	15	625 NM	620	0.8
CHI→ JFK	71	655 NM	635	3.1

(Weighted) Average % = 2.9%

Distance class 800-1200 NM

City Pair	Non-Stops/Day	By Jet Route	Direct	% Reduction
ST.L→NY	10	828 NM	770	7.0
DEN→SF	16	828 NM	818	1.2
NY→MINN	7	913 NM	895	2.0
NY→MIA	43	973 NM	953	2.1
DAL→MIA	4	1010 NM	975	3.5

(Weighted) Average % = 2.6%

Distance class 2000-2400 NM

City Pair	Non-Stops/Day	By Jet Route	Direct	% Reduction
NY→SF	14	2230 NM	2200	1.5

- Laying out direct routes between city pairs (FAA, airlines)

- Establishing the accuracy requirements of ground based and airborned equipment. Establishing the nature of the ground based equipment. e.g. Loran, VOR/DME, DVOR/DME (FAA)

- Logistics for the airborne systems to be borne by airlines.

The probability of implementing area navigation operations in future years, even without fuel conservation considerations, is high. Some programs underway point to implementation by 1977. Thus, it appears that the regulatory mechanism to implement area navigation is available. Some objections in the face of equipment costs may be posed by the airline industry. Alteration of fare structure or government subsidy may be a proper response to this objection. Necessary government funding to construct the routes, develop and install ground based systems, and to provide appropriate operating personnel would have to be available.

Current programs, if properly funded and manned, could result in implementation by 1977.

Costs

Disbenefits. The costs of onboard area navigation equipment ranges from about $2,000 to $150,000 per unit. Assuming an average cost of $40,000 per unit and a fleet of 2500 aircraft, then the cost to the airline industry would be $100,000,000. Assuming this sum amortized over 10 years and further assuming $10,000,000/yr for maintenance and spares, then the annual costs would be on the order of $20,000,000.

The costs to DOT for ground site construction, improvement, operation and maintenance, etc., will be considerable and is not estimated here.

Benefits. A major benefit to the airlines will be in fuel savings. Because of the net range reduction the net flying time will be decreased resulting in reduction of costs associated with flight operations. Assuming a total effect of 2% reduction, then the costs savings will be on the order of $42,000,000/year. For the airlines there could be a net cost benefit of about $20,000,000.

Barriers to Implementation

* Initial cost outlay for equipment.

3.5 Optimum Altitude Cruise

Concepts

For a given aircraft weight and speed there exists an altitude at which the fuel consumption is a minimum (fig 8). From an energy of conservation standpoint the aircraft's altitude would continuously be altered to conform with minimum fuel expenditure. At high altitude flight levels, aircraft are constrained by Air Traffic Control (ATC) standards to 4000 foot intervals and transition between intervals **after** receiving ATC permission.

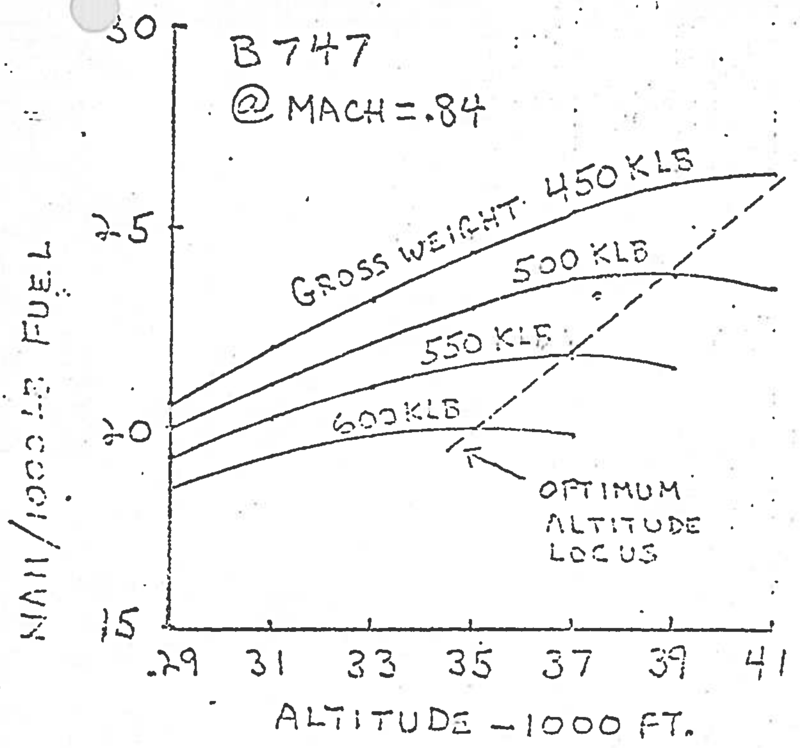
Fuel Consumption and Conservation

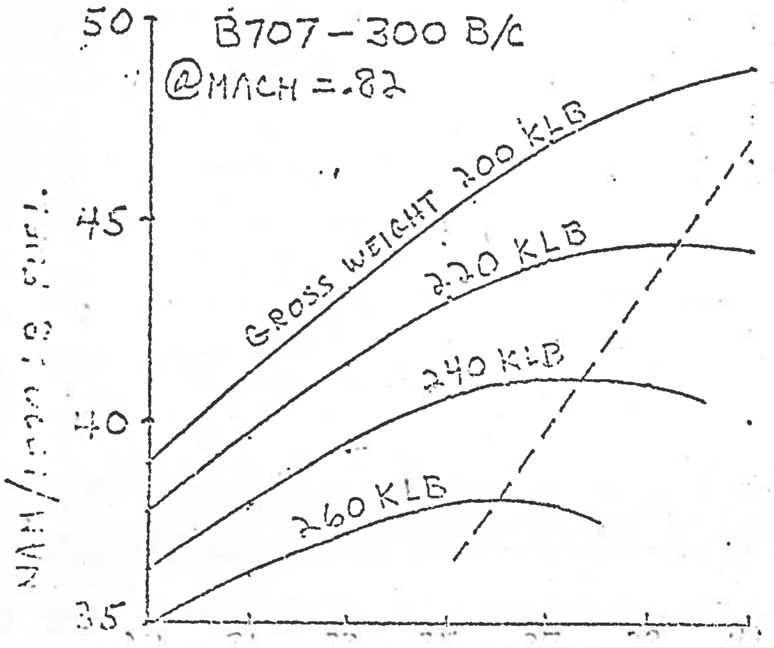
The penalty for flying off-optimum altitude is exhibited in fig 9. For all **three** types of aircraft the penalty is approximately 1% for alway flying 2000 ft and is approximately 3% for always flying 4000 ft off-optimum altitude.

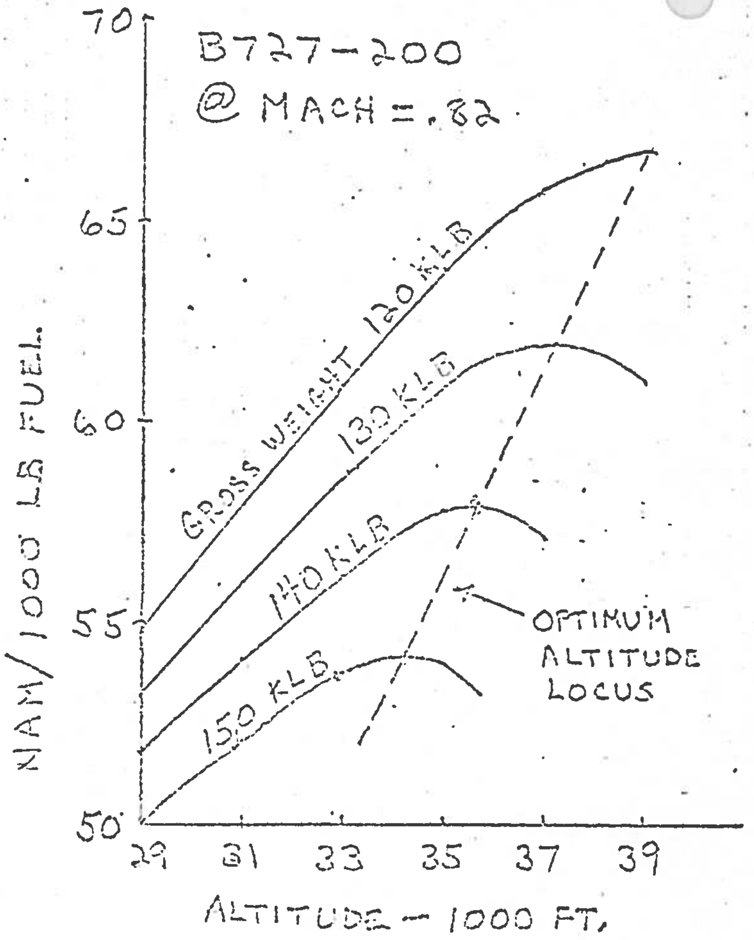
With flight intervals of 4000 ft the aircraft may fly so as to bracket the optimum altitude. This would result in an average off-optimum altitude excursion of 2000 ft and a consequent savings of 2% of fuel consumed during high altitude **cruise** flown at 4000 ft off-optimum.

If the flight intervals are reduced to 2000 ft and if the optimum altitude is bracketed, then the fuel consumed is further reduced to about 0.5% of the high altitude **cruise fuel** consumption.

In the current mode of operating at high altitude cruise levels pilots will request and **frequently receive permission to fly at a desired altitude. Assuming a**

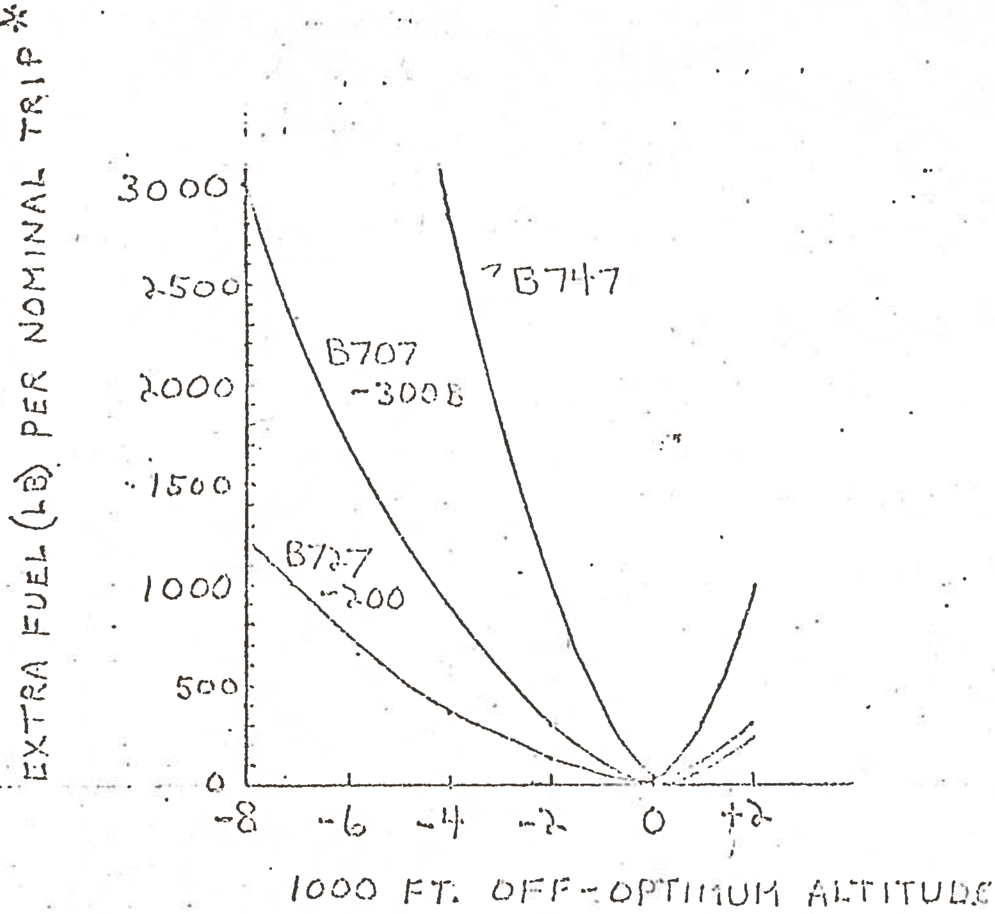






Specific Range Curve

Figure 8



*NOMINAL TRIP LENGTHS:

B727 : 550 NAM (LAND @ 130,000 LB)
B707 : 1200 NAM (LAND @ 205,000 LB)
B747 : 2000 NAM (LAND @ 480,000 LB)

Figure 9. Fuel Penalty for Off-Optimum Altitudes

frequency of requests granted at 80%, flight intervals of 4000 ft, optimum altitude bracketing, then about 1.6% of the nominal high altitude cruise fuel consumption will be used in flying off optimum altitude.

Instituting 2000 ft altitude intervals with an 80% permission granted frequency and optimum altitude bracketing, then the fuel consumed as a result of off optimum altitude flight would be reduced to % of total aircraft fuel. Tables 18, 19 reflect these savings.

Implementation Policy and Schedule

Since this measure should work to the benefit of the air carrier little difficulty should be encountered in securing unilaterial airline cooperation. The major procedural change should occur at enroute air traffic control centers operated by the FAA. Any applicable procedures to implement this measure could become part of FAA operating rules.

The policy may be implemented in 1975.

Costs

Disbenefits. One disbenefit may result from the addition of air traffic control personnel to handle an additional work load. However, the levels of automation currently being built into enroute traffic control centers could possibly accommodate any additional attention required by the centers without personnel addition.

Benefits. The major cost benefit will be a reduction in fuel costs in airline operations.

Table 18

Fuel Consumed During High Altitude **Cruise**

	Total Gallons per year x 10^6	Total Gallons per year Taxi-ing x 10^6	Total Gallons per year Air-borne x 10^6	Total Gallons per year Airborne above 20,000 ft x1
4-Engine Wide Body	540	16(2)	524	(90%)** 470
4-Engine* Reg Body	2938	126(3)	2812	(80%)** 2250
3-Engine Reg Body	2385	124(4)	2261	(60%)** 1357
2-Engine Reg Body	1309	80(5)	1229	(50%) 615
Total:	7172			

* Includes turbo jet hours

**Estimated total Airborne time

1 CAB Operating Cost Report, August 1972

(2) 1130 Gallons/Hr

(3) 750 Gallons/Hr

(4) 470 Gallons/Hr

(5) 310 Gallons/Hr

Table 19

Fuel Consumed by Flying Off Optimum Altitudes

	Total Gallons(1) per year Airborne above 29,000 ft x 10^6	Fuel Consumed Flying Off Optimum By 4000 ft x 10^6	Fuel Consumed(2) Flying Off Optimum By 4000 ft and Bracketing x 10^6	Fuel Consumed(3) Flying Off Optimum By 2000 ft and Bracketing x 10^6
4-engine Wide Body	470	14	8	4
4-engine Reg Body	2250	68	36	18
3-engine Reg Body	1357	41	22	11
2-engine Reg. Body	615	18	10	5
Total:		141	76	38
Ratio to Total A/C Fuel Consumption		2.0	1.1	0.5

[1] CF Table 1

[2] 4000 ft altitude intervals

[3] 2000 ft altitude intervals

Barriers to Implementation

- As operations increase in future years the assignment of appropriate altitudes may be more difficult to realize.

- Controller workload at centers may increase.

[Extended automation may minimize the effects of increased operations and workloads. Programs might have to initiated to insure proper automation.]

3.6 Reduced Ground Fuel Consumption

Concepts

An aircraft normally operates with all engines while moving over the airport surface. In addition the engines are normally on when the aircraft is in a waiting queue. Since movement over the airport surface is done at low speeds, it would be possible to shut down some engines during this surface movement and burn less fuel. It appears that partial shutdown for arriving aircraft only is feasible as an immediate measure.

The major surface queue is usually formed at the runway threshold by deparing aircraft. If these departing aircraft could be kept at the gate with engines off until the queue becomes reasonably small, then fuel would be conserved.

Fuel Consumption and Conservation

The fuel conserved during arrival taxiing with two engines of four and one engine of three off is approximately 67,000,000 gallons per year which represents approximately 0.75% of the total air carrier fuel consumed (Table 20).

The amount of fuel conserved by minimizing the queue has essentially been discussed as part of delay fuel minimization measure.

Table 20 Savings by Shutting Engines While Taxiing In*

	Total Gallons During Taxi (1971)	Total Gallons, Taxiing In	# Engines shut down	Total Savings Per Year (Gallons)
4-engine wide body	37×10^6	18.5×10^6	2	9×10^6
4-engine** reg. body	147×10^6	73.5×10^6	2	37×10^6
3-engine Reg. body	127×10^6	63×10^6	1	21×10^6

* domestic and international turbofan operations/cargo and passenger
**includes Turbojet operation, since these are significant

Implementation Policy and Schedule

Unilateral airline cooperation should be relatively easy to obtain to implement partial engine shutdown for arrival taxiing. The policy could be incorporated into airline operating procedures.

The measure could be instituted in 1974.

Costs

Disbenefits. Virtually no disbenefits.

Benefits. The major cost benefit will be a reduction of fuel costs in airline operations.

Barriers to Implementation

The formation of arrival queues on the surface could suggest an all engine on situation. Arrival queues would form where gate availability is a problem which would require more gates or improved gate scheduling.

4.0 Further Study

The objective of the study was to identify and assess fuel conserving measures applicable to air transportation. It was realized that within the approximate month and a half study period that an exhaustive evaluation would be difficult. The major thrust of the study, therefore, was to frame a basis for a further definitive study and evaluation that would result in meaningful, defensible policy.

It is felt that a future effort should basically have a threefold direction: (1) further detailing, confirmation, and expansion of the numeric results and implementation policy, (2) expansion of the study to include other affected segments of the air transportation industry, and (3) impacts of the air transportation fuel conservation measures upon other transportation modes. The nature and structure of these tasks are outlined below.

Task I. Expansion of the Analysis, Evaluation, and Feasibility of Each of the Measures and Others of Interest.

1.0 Identify and classify all conservation measures.

2.0 Structure each measure into the following format.

2.1 Fuel Consumption and Conservation. *For each measure quantify the amount of fuel consumed aperating in the applicable mode and the amount of fuel conserved by the measure implementation. Quantify for the years 1974, 1979, and 1990*

2.2 Equipment. *Identify types of airborne and groundbased equipment necessary for measure implementation. Identify the time scale for any development efforts and likely non-recurring and recurring costs.*

2.3 Operational Requirement. Identify and describe modifications and additions to airline and air traffic control operations necessary to implement measure.

2.4 Development Programs. Identify type and scope of government sponsored research, development, and test programs necessary to implement measure. Attach a cost value to program.

2.5 Implementation Policy and Schedule. Describe the policies and regulations prerequisite to implementation. Establish indices of merit for evaluation and monitor of measure implementation. Outline tax and fare policies that would enhance measure application. Establish a time scale for the sequence of actions leading to implementation of the measure.

2.6 Cost Benefits. Establish a format for determing cost benefits. This should include costs associated with airline operations and government programs. Determine method for realistically assessing costs to public.

2.7 Impact. Determine positive and adverse features associated with measure implementation. Determine and measure the intensity of the advantages and disadvantages to implemetation.

3.0 Load Factor Increase Measure. The load factor increase measure occupies a special position because: fuel saving potential appears to be greater than all the other measures combined and it affects the amount of fuel conserved by the other measures. Thus in addition to the items of Task I.2.0 special attention should be focused on:

3.1 Rejection Rate. Determine the statistical characteristics of the demand curve. Determine method for confirming statistical parameters from measured or existing data. Determine how the standard deviation may be changed. Establish a permissible rejection rate and document rationale.

3.2 Low Frequency Markets. Analyze low frequency markets. Establish a load factor increase measure in low frequency markets that accommodates the public, results in fuel savings, and is acceptable to the airline industry.

3.3 Competition. Analyze the effect of a load factor increase measure upon the competitive nature of the airline industry.

4.0 General

4.1 Demand. Establish and document demand projections for the 1974, 1979, and 1990 time frames. Establish high, medium, and low values for the given years.

4.2 Aircraft Mix. Establish technique for factoring aircraft mix into each fuel conservation measure. Estimate aircraft mixes for the years 1974, 1979, and 1990.

4.3 Tax and Fare Structure. Establish demand function curves for tax and fare structures. Determine effect upon demand. Establish method for factoring in tax and fare structure considerations into measure implementation.

Task II. Fuel Conservation Policies for Other Affected Segments.

1.0 General Aviation, Military.

1.1 Demand. Establish format for demand levels and numeric values for demand levels in 1974, 1979, and 1990.

1.2 Fuel Conservation Measures. Establish format for measure evaluation similar to that of section I.2.0. Determine and assess fuel conserving measures.

2.0 Other Segments. *Evaluate impacts of fuel conserving measures upon other groups or segments of interest and concern. These include: aircraft industry, labor, petroleum industry, foreign nations, etc.*

Task III. Intermodal Effects.

The fuel conserving measures will result in reduced BTU/passenger-mile consumption in airline operations. The consumption of fuel should be compared with those in other transportation modes. The comparison should be related to : fuel consumption, probability of implementation, cost benefits, impact upon gross national product, impact upon environment, etc. The adviseability of proportioning passenger flow into one transportaion mode or another should be determined. Tax and fare structures to realize these mode distributions should be examined. The effectiveness and role of legislation should be assessed.

The study, extending to the year 2000, should factor in transportation developments that appear to be feasible. These include developments in mass transportation, engine developments, new vehicle concepts, and fuel sources other than petroleum.

Study Assumptions and Bounds

Appendix A

APPENDIX A

1.0 Introduction

The referenced documents contain, in general, the assumptions and rationales that led to both the numeric conclusions and implementation policy. It is felt that these are sufficiently detailed to permit critical review of the conclusions presented in this summary document. Two relatively important considerations are presented in this appendix: rejection rate computation and magnitude of delay computation. These considerations are isolated because they: (1) deal with measures which can ostensively result in large fuel savings (load factor increase and delay reduction) and (2) are not usually encountered in the literature.

The referenced documents also contain the bounds or limitations to the study for each measure. As is usually the case with such bounds, they are, essentially, implicitly stated. This appendix briefly discusses these limitations and bounds. The suggestions for further study (section 4.0) are intended to extend these bounds.

Added to this appendix is a sub-appendix - appendix A-1. This sub-appendix discusses the concepts of airport capacity and delay.

2.0 Passenger Rejection Rate as a Function of Load Factor

Introduction.

Increasing the load factor is a relatively simple and effective measure to conserve air transportation fuel. However, increasing the load factor on a given flight tends to increase the number of potential passengers that will not be able to board that flight. That is, as the load factor increases, the rejection rate increases. The underlying assumption leading to this phenomenom is the probabilistic nature of the demand for flight.

Probabilistic Concepts.

Assume that the demand, i.e., passengers requesting seats, is normally distributed (figure 1) with a mean, m, and a standard deviation, σ. The probability density function is

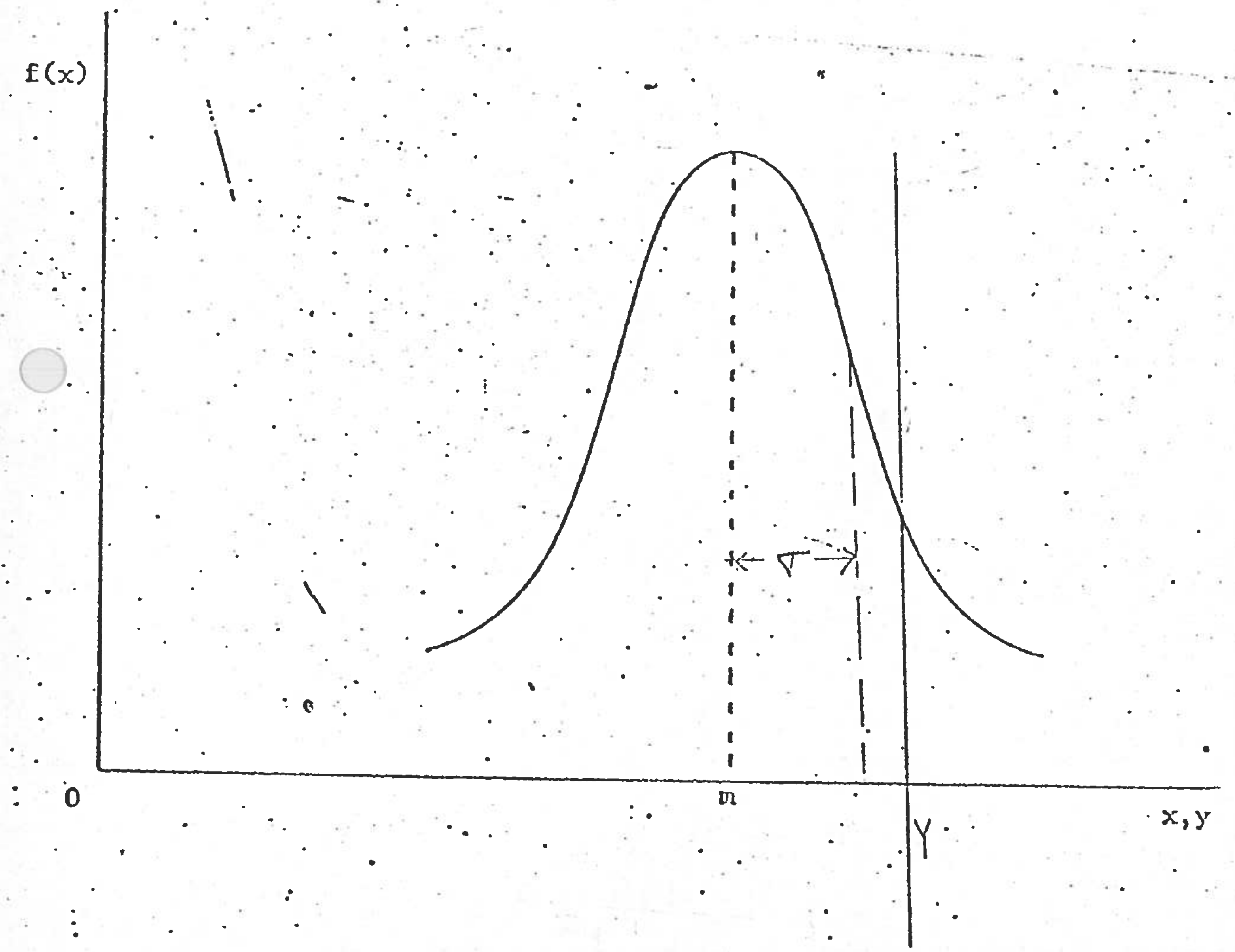
$$1. \qquad f(x) = \frac{e^{-\frac{(x-m)^2}{2\sigma^2}}}{\sqrt{2\pi}\,\sigma}$$

The average number of people who will be accommodated, i.e., will fly, may be expressed as (ref 5)

$$2. \qquad F_{av} = \text{(Probability Plane Fully Loaded)} \times \text{Seating Capacity} + \text{(Probability Plane Not Fully Loaded)} \times \text{(Average Number of Passengers When Not Fully Loaded)}$$

More succincty, the average number that fly may be expressed as the expectation function

$$3. \qquad F_{av} = E[\, g(x),\ f(x)\,]$$



Normal Probability Density Function

Figure A-1

where g(x) describes the number of passengers accepted.

The load factor is simply the average number of passengers who fly ratioed to the seating capacity:

4) $$LF = \frac{F_{av}}{Y}$$

where Y is the seating capacity.

Similarly the average number of passengers that is rejected is the expectation function

5) $$R_{av} = E[\, h(x),\, f(x)]$$

where h(x) describes the number of passengers rejected.

In evaluating these expectation functions it is necessary to solve an expression of the form

6) $$\int_{-\infty}^{Y} x\, f(x)\, dx = \int_{-\infty}^{Y} \frac{x\, e^{-\frac{(x-m)^2}{2\sigma^2}}}{\sqrt{2\pi}\,\sigma}\, dx$$

By employing the derivative of the function f(x) equation 6 becomes

7) $$\int_{-\infty}^{Y} x\, f(x)\, dx = -\sigma^2 f(x)\Big|_{Y} + m\int_{-\infty}^{Y} f(x)\, dx$$

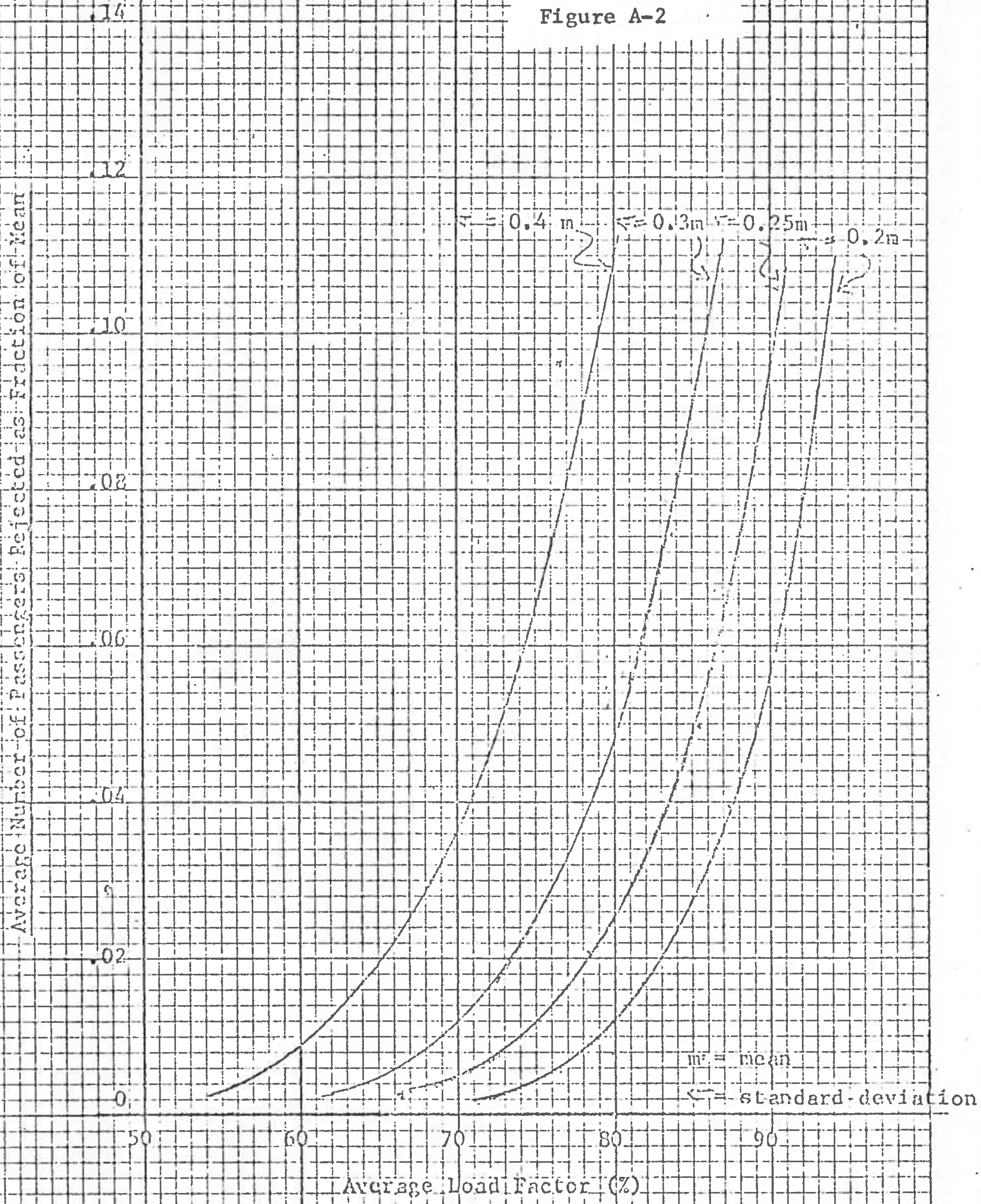
and the standard tables may be used.

Results

The average number of passengers rejected as a fraction of the mean is plotted in figure 2 against load factor for different values of standard deviations. If we consider the current demand density function to be characterized by a standard deviation of 0.4 times the mean, then on the average about 5 passengers in 1000 would be rejected with load factor on the order of 56%. The number of passengers rejected increases rapidly as the load factor is

Rejection as a Function of Load Factor

Figure A-2



increased with a given standard deviation. As an example with a standard deviationof 0.4 of the mean and a mean value of 1000, then about 20 passengers would be rejected with a load factor of 65% and about 40 passengers rejected with a load factor of 71%.

Obviously to retain a low rate of rejection as the load factor is increased it would be necessary to reduce the standard deviation of the distribution. As an example decreasing the standard deviation to 0.3 of the mean from 0.4 of the mean permits an increase in load factor from about 57% to 65% while ~~x~~ retaining the same rejection rate of about .005 of the mean. Reducing the standard deviation further to 0.2 of the mean permits a load factor of about 76% with the same rejection rate.

Precisely what a reasonable rejection rate should be and how to engineer a smaller standard deviation to the demand distribution will be examined in he next phase of the study.

3.0 Delay Reduction

As a result of airport congestion the concept and measurement of aircraft delay has received considerable attention. Appendix A-1 discussed some of these concepts. As discussed in this sub-appendix, a central problem in determining delay in future years is that of factoring in advances in air traffic control without the use of extensive simulation programs. A relatively rapid technique has been generated (Appendix A-1, reference 3, 6, 7) and used as the basis for the computation of delay magnitudes. The values used for delay per operation in the years 1974, 1979, and 1990 represent compromises from the values stated in references 6 and 7 and computed for the years 1971, 1984, and 1995. It was felt that the demand variations among the years 1971 - 1974, 1979 - 1984, and 1990 - 1995 would not be significant and that the premises underlying the computation were sufficiently broad to permit the correlation. It was also felt that such compromises and correlations fit within the context of this study.

Accordingly, for this preliminary study the values used for the key assumptions - delay per operation - were; (Table 10 main text)

	1971-1974	1970-1984	1990-1995
Delay per Operation (minutes)	1.58	0.98	9.0

Delay per operations w/o Fuel Conserving Measures

Table A-1

The delay per operation is dependent (Appendix A-1) upon the number of operations. Thus when the load factor is increased the number of operations are decreased and the delay per operation is decreased. For this study, the values were: (Table 11 of main text)

	1971-19774	1979-1984	1990-1995
Delay per Operation (minutes)	1.0	.6	.98

Delay per Operation with load Factor Increase

Table A-2

4.0 Study Bounds and Assumptions

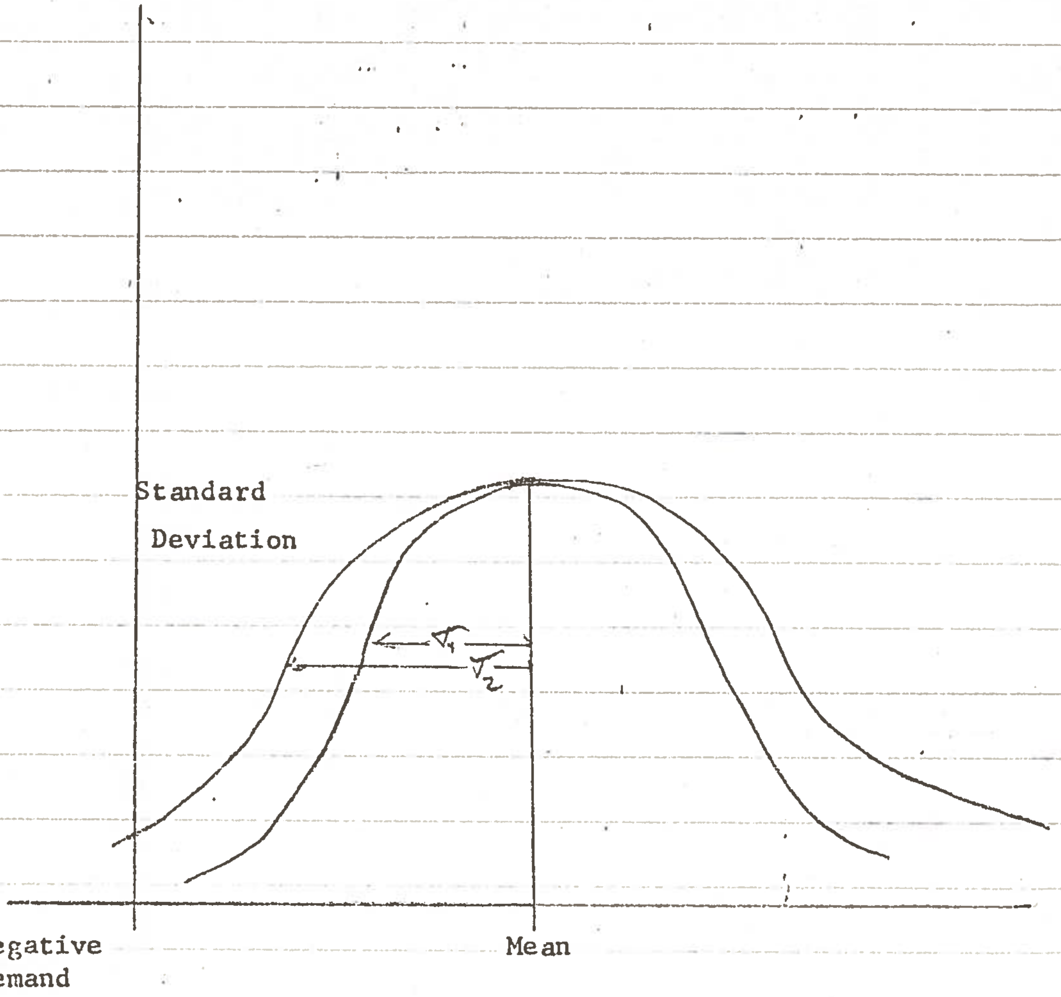
The study bounds limitations and assumptions may be classed as unique to a fuel conserving measure - specific - and as applicable to all measures - general. The suggested further study program (section 4.0) will, if conducted in depth, extend the bounds and remove the limitations. This section discusses the specific bounds first and then the general bounds.

Load Factor Increase

Rejection Rate. A normal probability density function is assumed for passenger demand. While a statistical approach would suggest a normal probability distribution, the actual demand might be skewed. This skewness is supported by the condition that as the standard deviation becomes a larger fraction of the mean the demand becomes negative (figure 3). A negative demand might be interpreted as mathematically appropriate but its practical meaning is unclear.

Standard deviation values ranging from a 0.28 to 0.4 of the mean were assumed as likely values. There does not appear to be any definitive reports of actual standard deviation values. In private conversations values as low as 0.2 of the mean for business travel have been quoted.

In support of load factors in excess of 65% it was assumed that a smaller standard deviation, i.e., down to about 0.25 of the mean could be engineered. Exactly how this may be done is unclear and appears properly to be a major study effort in itself.



Effect of Spreading of Normal Curve

Figure A-3

Rejection rates on the order of 2% were assumed permissible. If the rejection rates could be raised, for a given demand distribution characteristics, then the load factor could be increased. A study effort would be required to determine permissible rejection rates.

Low Frequency Markets. In low frequency markets - two/day or less - it would appear that reducing flights would not be in the best public interest. Two methods were suggested for increasing load factor in these markets: use of different aircraft and multistop scheduling. Both of these techniques, among others, have to be examined market by market, or in representative markets, to determine their feasibility as load factor increase methods.

Competition. Increasing the national load factor would require agreement among the airlines. Such agreements distort the competitive nature of the industry. How the airline industry will function under heavy regulation has to be thoroughly aired and policy determined.

Delay. The magnitude of delay was based on approximate methods for predicting delay in an improving air traffic control system. The approximations need to be examined in closer detail.

Cruise Speed. Essentially three aircraft types were examined at primarily one altitude. An average value of cruise speed and an average fuel savings was assumed. It would be necessary to examine other types of aircraft, determine current cruise speed conditions, and establish cruise speed for fuel conversation purposes.

Optimum Altitude Flight. Determining fuel conservation while operating at optimum altitude is straightforward. However, the impact upon air traffic control operations is unclear. This effect has to be examined in closer detail.

Ground Fuel Use. The study should be expanded to include more detailed investigation of engines off during departure taxi.

General

Cost Benefits. Cost benefits and disbenefits were examined in a preliminary fashion. A structure for determining cost benefits should be established and agreed upon. The data used in determining cost benefits should be more extensively researched. Costs to the government to implement these programs should be examined.

Tax Structures. The use of taxes to realize a measure implementation was not examined. It is evident that a tax scheme that penalizes the fuel user would tend to insure implementation. However, the balance between taxes, fare levels, operating costs, etc., should be examined before a tax position is established.

Fare Structure. The airlines should increase their profits through introduction of fuel conserving methods. It would be reasonable to assume that these profits, where excessive, would be passed on as fare decreases. These fare reductions would impact upon the traveling habits of the public with an unkown effect upon total transportation energy. These effects were not examined.

Aircraft Mix. The aircraft equipment serving various markets may be altered to reduce the number of flights while satisfying public demand in an optimum fashion. The effect of aircraft mix was not examined.

Capacity and Delay

Appendix A-1

1.0 CAPACITY

Capacity Expressed as Runway Capacity

The capacity of an air traffic control system is measured by the number of aircraft operations that the system accommodates. Historically the capacity of the airport system has been recognized as the limiting element in the expression of air traffic control capacity. There are a number of probable reasons that the airport system dominates the capacity evaluation of an air traffic control system. Whatever the strength of these reasons it is convenient to express the concepts of of capacity and delay within the framework of terminal area operations.

The capacity of an airport system is the ability of the terminal system complex to move aircraft into and out of the terminal area. The terminal complex controlling these operations consists of controllers, navigation aids, communication links and surveillance devices operating within a set of rules and procedures. The region of movement extends from the terminal area airspace boundary over the runway the taxiway complex.

Since all airport operations funnel through the runway complex, it is convenient to describe the airport capacity as a runway capacity while recognizing that capacity is affected by non-runway situations such as departure airspace restrictions, taxiway-runway crossings, etc.

Capacity Determinants

The capacity of an airport system is essentially determined by four elements and conditions.

- Runway, taxiway configurations
- Navigation aids, communication links, surveillance devices, controller capabilities, and automation levels
- Weather conditions
- Type of aircraft served.

A set of operating rules and procedures has been devised to account for these elements. There are five such basic rules and procedures.

Rules Affecting Capacity

There are 5 basic rules and procedures affecting a runway capacity.

#1 Minimum separation criteria between arriving aircraft

#2 Minimum separation criteria between departing aircraft

#3 Minimum separation criteria between departures and arrivals

#4 Priorities assigned to arriving and departing aircraft

#5 Prohibition of moving aircraft on a single runway at the same time

There are a number of different aircraft using the airport system. These aircraft possess diverse arrival speeds, deceleration characteristics, takeoff speeds, etc, which affect the capacity of the airport system.

For the large number of aircraft that might be using the runway system, the resulting varying capacity would make evaluation of airport capacity unwieldy. The nominal approach is to assume a mix of aircraft classes using the airport runway system and to average the effects of this mix into an average capacity. In general large hub airports accommodate a high percentage of larger jet aircraft. In this situation, percentage variation of the jet aircraft class does not have a prounounced effect upon the capacity.

Illustration of Rules, Mix Effects

The net effect of all the airport system elements contributing to airport capacity is reflected in the service time to the arriving and departing aircraft. More accurately it is the interval between those time points that the airport system will permit aircraft to enter the service stream. Consider three aircraft entering a terminal from three different directions. They will all land on a single runway. At some point in the airspace, e.g. the outer marker, they will merge along a common path separated in trail. Assuming a common path from an outer marker 6 nm from threshold and a single runway and taxiway to an apron and assuming further for the first two aircraft:

- an approach speed of 140 kts
- a runway deceleration of 6 ft/sec^2
- a 15 kt exit existing at the point the aircraft decelerates to 15 kt
- a taxi speed of 15 kts
- a taxi length of 1 nm

then the 1st aircraft will cover the common distance in 430 seconds. Assuming that the 2nd aircraft was constrained to be 3 nm behind the 1st aircraft until the 1st aircraft touchdown (rule #1) then the 2nd aircraft would reach the threshold 77 seconds after the 1st aircraft. Since the 1st aircraft has cleared the runway - i.e. runway occupancy is 35 seconds - the rule prohibiting simultaneous runway occupancy (rule #5) is not violated. The 2nd aircraft will arrive at the apron

77 seconds after the 1st aircraft. Thus, the airport system could service arriving aircraft of the same class in a time interval of 77 seconds or at a rate of about 47 per hour.

If the 3rd aircraft were a lighter aircraft with an approach speed of 120 kts, it might be necessary to stretch the separation distance to, say, 5 nm because of wake vortex conditions. Thus the 3rd aircraft would reach the runway threshold 150 sec after the 2nd aircraft. The service time for the slower aircraft would be almost twice as long as that for the faster aircraft. The total time elapsed from when the 1st to 3rd aircraft passed a common point, e.g., runway threshold, starting with the 1st aircraft 3 nm from the threshold, is 304 seconds. This corresponds to an arrival rate or capacity of about 36 aircraft per hour.

Correspondingly a departure-departure spacing of, say, 39 seconds would result in a departure capacity of 92 aircraft per hour (rule #2). If departures are interleaved with arrivals on a single runway, i.e. the sequence is departure-arrival-departure-arrival, etc., then the net effect is usually a reduction in either the arrival or departure capacity. Assume an arrival followed by a departure and an arrival on a single runway (rule #4) and that the departure cannot be released unless the following arrival is at least 2 nm from runway threshold (rule #3). Further assume that the approach speed and liftoff speed are 140 kts and that the aircraft accelerate and decelerate at 6 ft/sec^2 on the runway. The 1st arriving aircraft touches down and occupies the runway for 35 seconds. At this point, but not before (rule #5), the departure may be released; however, the next arriving aircraft must be 51 seconds from touchdown. The total time between the 1st and 2nd arrival is 86 seconds during which one arriving aircraft and one departing aircraft have been services. Thus, with 2 operations in 86 seconds, the single runway system is operating at a net capacity of 84 aircraft per hour. Thus, the departure-arrival spacing, single occupancy, and interleaving (rules 3, 4,5) have been serve to reduce the capacity when the situation is that operating with departures only.

The capacity numbers used thus far have not accounted for non-ideal conditions in the airport system operation. Such non-ideal conditions include:

- uncertainty in aircraft touchdown point
- variations in approach speed about nominal
- a finite number of runway exits requiring the aircraft to taxi along runway to a variable exit
- congestion along the taxiway system
- common departure path

These, and a number of other conditions geneally result in capacity numbers much less than quoted in the above examples.

Capacity Models

There are at least two ways to describe or model the capacity of an airport system: maximum throughput rate and capacity-delay. The maximum throughput rate is the number of operations, arrivals and departure, that the system can handle or service. It is also assumed that aircraft are always available to be serviced; i.e. there is always at least one aircraft in in the departure or arrival queue. The maximum throughput rate is termed the saturation capacity.

The capacity-delay is a measure of the system's ability to service arrivals and departures such that the average delay to the aircraft over a given time interval is within a defined limit. Since delays are magnified during airport busy periods, it is usual to define an acceptable delay over the busy hour periods, i.e. when the demand rate is normally at the maximum for the day.

2.0 DELAY

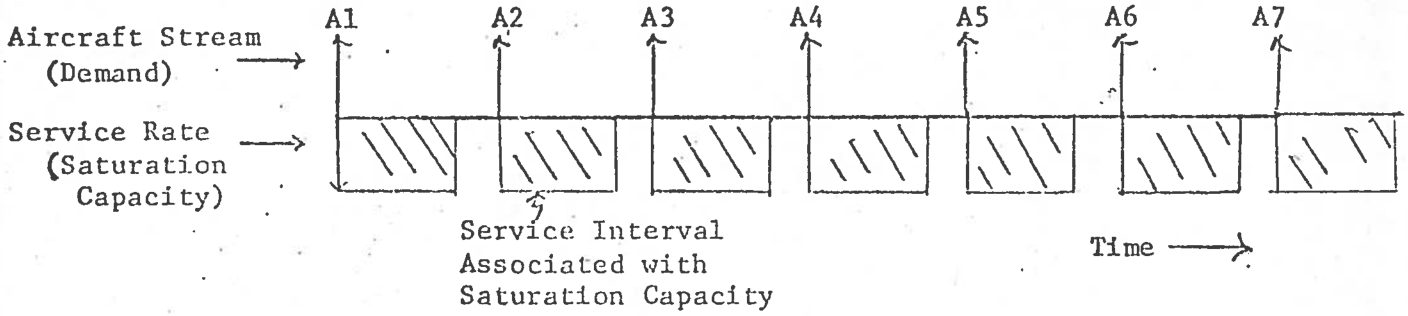
Aircraft delay, as employed within the context of terminal area operations, is the difference between the nominal aircraft transit time and the actual transit time over the region of movement. The region of movement includes the terminal airspace and the runway-taxiway system. It is bounded on one side by the gate apron and on the other side by the terminal area boundary. The region of movement is usually reduced for analysis and modeling purposes. For incoming aircraft the region of movement stretches from the start of a common path over the runway and taxiway complex to the gate apron. For departing aircraft, the region of movement extends from the gate apron over the taxiway-runway complex into departure airspace. If there are a number of departure routes, i.e., the departure airspace is unrestricted, then the departure region of movement may terminate shortly after liftoff. If the departure airspace is restricted to a single or few departure routes - as may be the case in noise abatement procedures - then the departure region of movement may extend out to the terminal area boundary or handoff.

The nominal transit time for an arriving aircraft, within the model, is the time it would nominally take (1) to fly from some outer marker at a nominal approach airspeed to runway touchdown, (2) decelerate at a nominal deceleration to an exit speed, and (3) taxi at a nominal speed over the taxiway system to the gate apron. The nominal transit time for a departing aircraft is the time it would nominally take to (1) taxi over the taxiway system at nominal taxi speed to the runway, (2) to roll along runway at nominal acceleration to liftoff and (3) to fly at nominal airspeed some distance along the departure route. Disruptions to these movements, or departures from the nominal, are accounted as delays attributable to the air traffic control system. Delays due to other sources, such as airline operations, are not included. Thus, delays due to gate unavailability, aircraft equipment malfunctions, etc., while real, are not counted as part of the air traffic system delay.

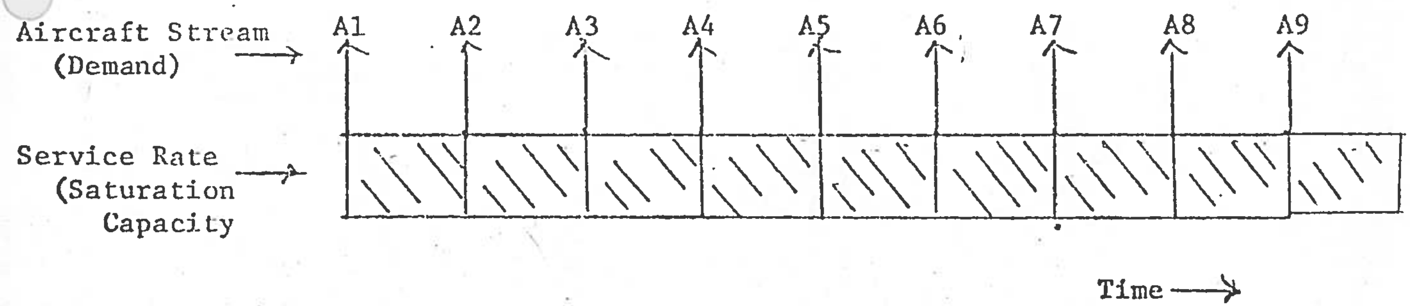
Delay and Scheduled Aircraft

If all the aircraft in the terminal area were properly scheduled, and the aircraft held to these schedules, then the airport could operate at its saturation capacity. That is, a time to initiate roll for takeoff is reserved for departing aircraft and time to touchdown is reserved for an arriving aircraft. The departing aircraft would leave its gate at a scheduled time, and depart the terminal system at the scheduled time. Similarly an arriving aircraft would reach the outer marker or gate, touch down, exit runway, and arrive at the apron at prescheduled times.

Under this condition, no aircraft would experience a delay (Fig 1). Obviously if the demand were less than the saturation capacity and each aircraft would perform to an imposed schedule, there would be no delays, Thus, in figure 1 the time interval between initiation of service time is always greater than or equal to the minimum service time.



Demand Rate at Less than Saturation Capacity (No Delay)



Demand Rate at Saturation Capacity (No Delay)

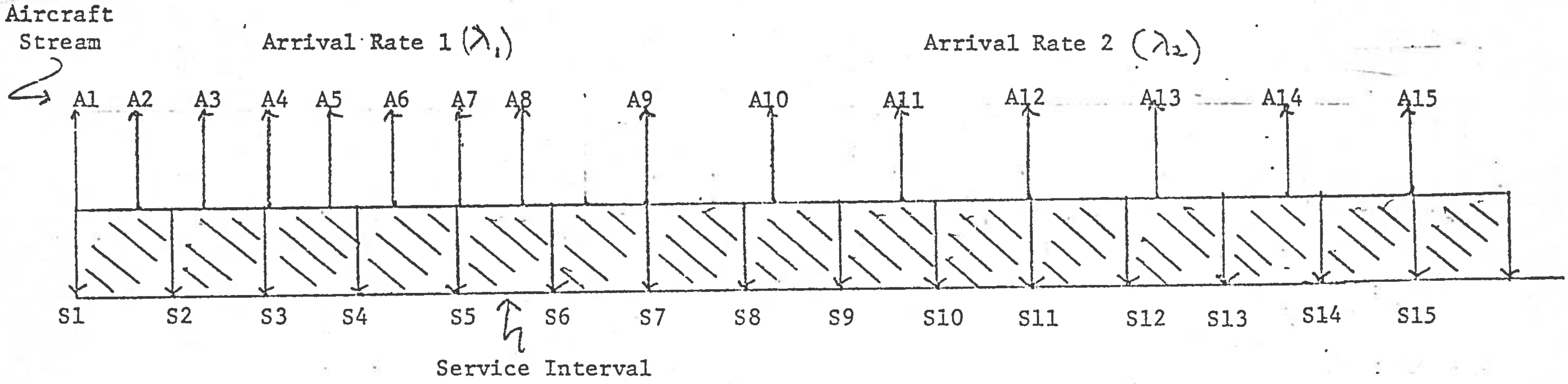
Figure 1.

If all aircraft arrive at their scheduled times but the interval between these scheduled times were less than the service time then the aircraft would be forced to wait in a queue. For arriving aircraft this queue might be in the form of holding patterns about the airport; for departing aircraft this queue might be a string of aircraft lined up at the end of a runway. For the queue to disappear the demand would have to slacken off to a rate less than the capacity. Thus the aircraft in the queue would experience delays until all the aircraft are capable of being serviced immediately upon demand, i.e. until the queue is empty. In fig 2 aircraft arrive at a rate λ_1, which is greater than the capacity, and then at a rate λ_2, which is less than capacity. The 1st aircraft experiences no delay. The 2nd through the 14th aircraft experience delays and the 15th aircraft experiences no delay, i.e. the queue is empty. By inspection of Fig 2 the maximum number in the queue, i.e. waiting to be served is two and aircraft #8 experiences the largest delay. By summarizing over the individual delays a total delay may be obtained, which, when divided by the number of aircraft yield, the average delay. In the example quoted above, the 1st group of aircraft arrive at a rate of λ_1, which is greater that the capacity, μ, of the system. The 2nd group arrives at a rate, λ_2, which is less than the capacity. The total delay is

(1)

$$D = \left(\frac{1}{\mu} - \frac{1}{\lambda_1}\right)\frac{H_1(H_1-1)}{2} + \left(\frac{1}{\mu} - \frac{1}{\lambda_2}\right)\frac{H_2(H_2+1)}{2} + (H_1-1)H_2\left(\frac{1}{\mu} - \frac{1}{\lambda_1}\right)$$

μ - saturation capacity
λ_1 - arrival rate for 1st group



Sn — Time of Initiation of Sercice for
nth Aircraft (An)

Overcapacity and Undercapacity Scheduled Arrivals

Figure 2.

λ_2 - arrival rate for 2nd group
H_1 - number of A/C in 1st group
H_2 - number of aircraft in 2nd group

The average delay for this example is

$$D_{AVE.} = \frac{D}{H_1 + H_2}$$

As an example if the saturation capacity were 60 per hour and the 1st group of 8 aircraft arrived at a rate of 90 per hour and the 2nd group of 6 aircraft arrived at 45 per hour, then the total delay is 16.3 min and the average delay 1.25 min.

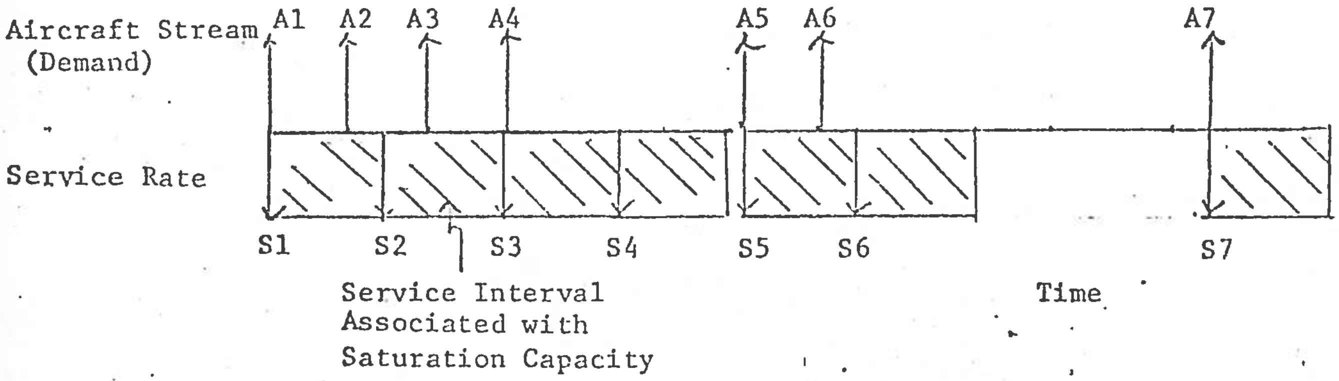
Random Arrivals

Arriving and departing aircraft, in general, do not demand service in an ordered, scheduled fashion. To an observer of the airport operations it would appear that the aircraft arrive or request service in a random fashion. Such randomness leads to individual aircraft delay even when the number of aircraft requesting service over a time interval is less than the number that the airport system can handle. In fig 3 the average number of aircraft over the same time interval, or the average demand, is one-half the saturation capacity. However when the same number of aircraft arrive randomly over the same interval some individual aircraft experience delay. Thus, even for arrival rates less than capacity an accummulated delay and an average delay may be obtained. In the example of fig 3a the delays would be incurred by aircrafts #A_2, A_3, A_4, and A_6 and the total delay would be

$$D = (S_2 - A_2) + (S_3 - A_3) + (S_4 - A_4) + (S_7 - A_7)$$

Figure 3

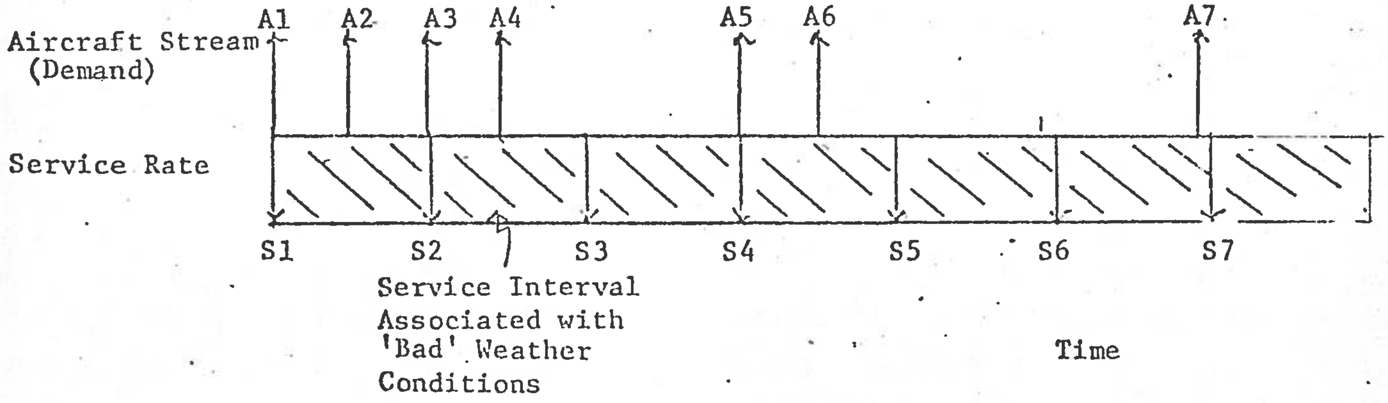
Effect of Random Spacing at Less than Capacity



Aircraft A2, A3, A4, and A6 are delayed

Effect of Random Arrivals

Figure 3a



All Aircraft are delayed

Effect of 'Bad' Weather with Random Arrivals

Figure 3b

and the average delay per aircraft over the interval would be

$$D_{ave} = \frac{D}{7}$$

Where arrivals are random the delays will be determined by the probabilities characterizing the arrival process. It is generally agreed that the arrival pattern conforms to a Poisson process. This underlying observation brings the formidable elements of queuing theory into play.

The familiar and manageable expressions of queuing theory generally deal with steady state conditions. The actual operation at an airport has to deal with demand levels that vary over the day. During the morning hours the number of operations is high for approximately a two hour period. This activity tapers off to a low around midday and peaks again for a 2 hour period in the late afternoon and early evening and then tapers off to little activity during the late night and early morning hours. The arrival rate has been approximated by a sine curve with a period of one-half day.[1]

Analyses of these types of demand show little transient effect. Therefore, the relatively manageable expressions of steady state theory, with minor modifications, may be brought to bear upon the analysis.

Queuing Expressions and Airport Delay

A typical queuing process is illustrated by the operation at the bank teller's window. Customers arrive at the window in a random fashion where the bank teller performs his financial service. If these customers had sapced their arrivals to correspond with the teller's service time, then no one would have to wait. However, they arriva in random fashion and a waiting line or queue builds up at the teller's window. The process is characterised by an arrival pattern, a service mechanism, queue discipline, and a number of servers.

The arrival pattern in this process is a Poisson arrival pattern characterized by an average arrival rate. That is, while the individual arrivals and interarrival times follow probabilistic distributions, a number of arrivals averaged over a period of time (λ) is a basic value in the probability expressions. Some of the key concepts characterizing the arrival pattern are: (1) the probability of a given event occurring in a small time interval follows a uniform distribution ($= \lambda \Delta t$); the probability that n events occur over a time interval follows a Poisson distribution ($= e^{-\lambda} \frac{\lambda^n}{n!}$); the probability that the time between events is less than a given value follows an exponential distribution (probability density function $= \lambda = e^{-\lambda t}$).

The service process may also be characterized by probability expressions and expressed in terms of means and variances. The form of variance may take on an Erlangian distribution. This distribution may be thought of as a convenient method to fit the observed variance between the 2 extremes of (1) a constant service time and (2) an exponential service time.

The queue discipline refers to priority of service. Some examples of queue discipline are first in, first out; or last in, first out; or service in random order. The number of servers or channels is self-explanatory. In the bank example one teller represents one server or channel, 2 tellers represent 2 servers, etc.

A shorthand notation describing the process has been developed in the form of A/B/n. Where A refers to the arrival process, B the service process, and n the number of servers. The letters used are:

M - an exponential interarrival time
G - general service time (includes Erlang)
D - constant service time (variance is zero)
E_k - Erlangian distribution (k is an integer)

Thus M/G/1 denotes a Poisson arrival, a general service time, and one server.

In the airport problem the arriving and departing aircraft form the Poisson arrival process. They are served by a runway system with a mean service time which represents the saturation capacity. There is some question as to whether the service has a zero variance or an Erlang distribution. The use of a general service time can blanket the variance issue where the values used in a particular instance may be justified on endemic grounds. A single server model and a first in, first out queue discipline is assumed.

Some steady state queuing expressions of interest for M/G/1 situation are:

$$\rho = \frac{\lambda}{\mu}$$

$$W = \frac{\rho^2}{2(1-\rho)}\left[1 + (\sigma_s \mu)^2\right]$$

$$D_{AV} = \frac{\rho}{\mu 2(1-\rho)}\left[1 + (\sigma_s \mu)^2\right]$$

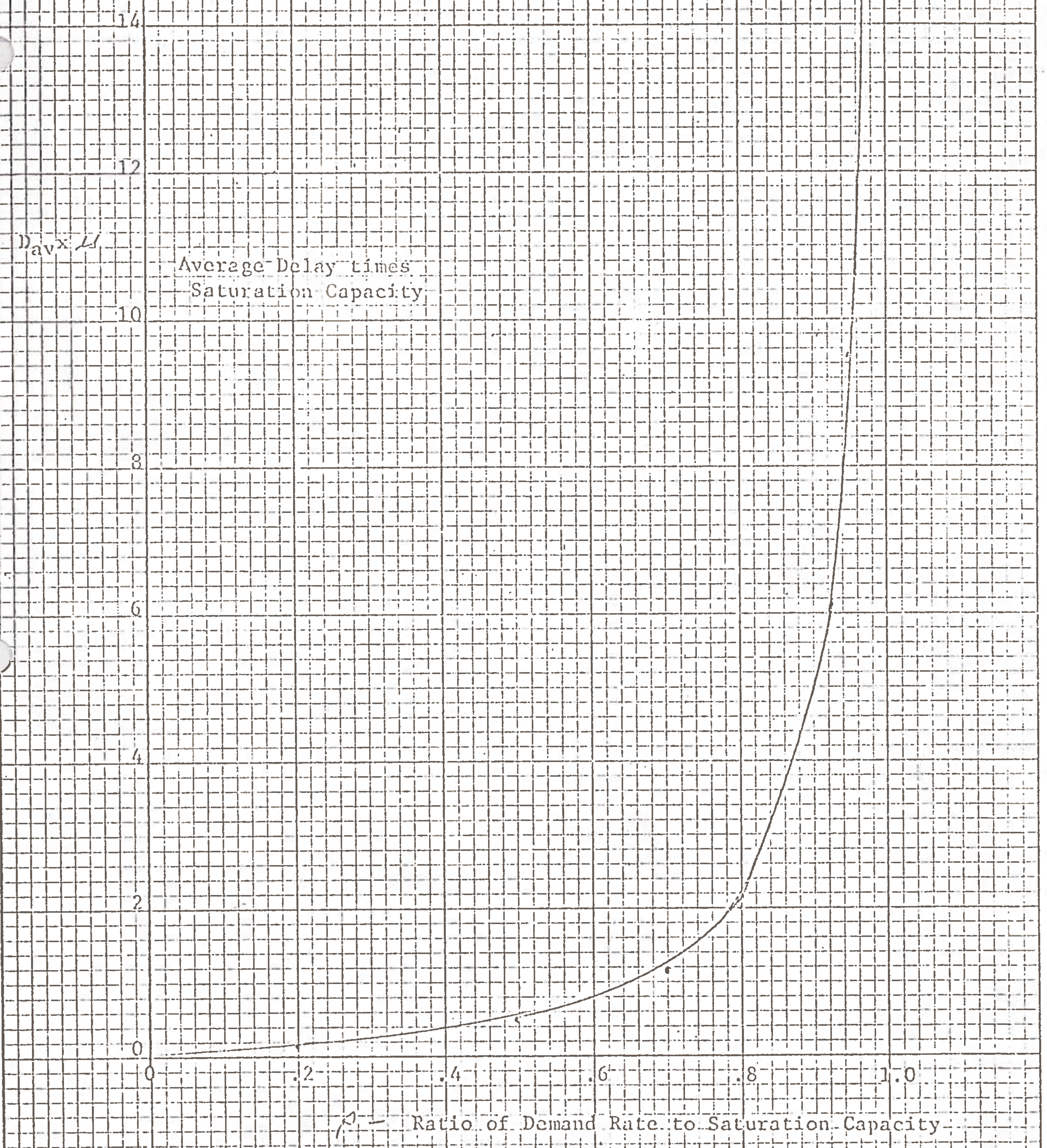
where the symbols denote

Symbol	Queuing Theory Related	Airport System Related
λ	average number of arrivals/time	demand in operations per hour
μ	inverse of the mean service time	saturation capacity ops/hr
w	mean of the number of items in the queue (excluding item being serviced)	mean of the number of aircraft waiting in the arrival, departure queues
D_{AV}	mean of waiting time in the queue (excluding serviced time)	average delay to all aircraft
σ_s	standard deviation of the service time	standard deviation of airport system servic time

The driving parameter is the $(1-\rho)$ expression of the denominator. Fig 4 plots the average delay for the constant service time ($\sigma_s = 0$) through the expression

$$\mu D_{AV} = \frac{\rho}{2(1-\rho)}$$

With a saturation capacity of 60 opns/hr then an arrival rate of 53.3 per hour would result in an average delay of 4 minutes. However, a very small increase in the arrival rate would produce large increases in the average delay. As an example an arrival rate of 56 opn/hr would result in an average delay on the order of 7 minutes.



Average Delay in Poisson Process with Constant Service Time

Figure 4.

The capacity-delay model that expressed the runway capacity as a reasonable level of delay is based on the concept of Poisson arrival distribution. This distribution, in the delay computation, has been considerably modified to include numerous airport phenonema and observed airport operations. The result has been catalogued in a handbook[2,3] that currently forms the cornerstone for computing airport capacity. This handbook is a collection of figures, charts, tables, and procedures that ostensibly could be used by people with diverse backgrounds.

In order to compute delays with the saturation capacity or maximum throughput model it would be wise, if not necessary, to simulate the operation in a computer program. It is possible to correlate the saturation capacity with the capacity-delay model if one assumes the saturation capacity inversely proportional to the service time in the expression:

$$\lambda = \frac{K \mu^2 D_o}{1 + 2\mu D_o}$$

where D_o - acceptable level of average delay
k - an empirically fitted constant

In this case λ represents the capacity of the capacity-delay model. It is then possible to enter the charts and tables of the handbook to arrive at annual capacity and annual delay values.

Scheduling with Gaussian Distribution

As discussed earlier in this appendix if all the aircraft would arrive at selected points in the terminal region of movement at appropriately scheduled times, the airport may operate at its saturation capacity with no delay to the operations. Even in this operation mode it is difficult to conceive that each aircraft would arrive at these points at exactly the proper time. One would anticipate a statistical distribution of arrival times and further anticipate that the distribution in gaussian in character (fig 5a).

While a detailed analysis is beyond the scope of this appendix, it is possible to infer some general effects from this situation.

Assume a 'worse' case of a sequence of aircraft pairs where the 1st arrives 3 sigma later than its scheduled time and the 2nd arrives 3 sigma earlier. If the airport system were to accommodate all the aircraft without delay, then the scheduled intervals between arrivals would have to be increased by 6 sigma. Thus, if saturation capacity were 60 ops/hr or a service time of one min, then for a 1 sigma value of 5 sec, the aircraft would be scheduled to arrive at intervals of 1.5 minutes. This would mean a scheduled operation of 40 ops/hr or 0.666 efficiency if each aircraft would experience no delay. The governing expression is:

$$C_o = \frac{1}{\frac{1}{C_j} + 6\sigma}$$

C_o - scheduled operating level for no delay
C_j - saturation capacity
σ - standard deviation about scheduled arrival

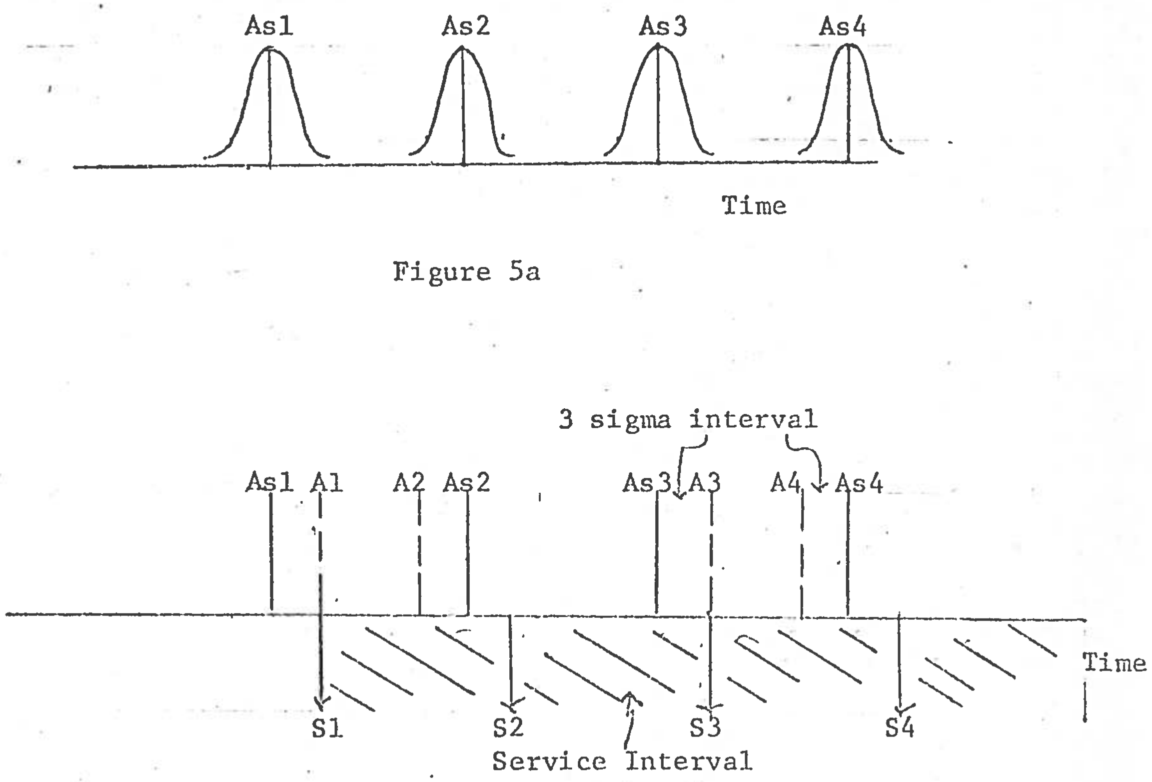


Figure 5a

Figure 5b

Asn - Scheduled Arrival of nth Aircraft

An - Actual Arrival of nth Aircraft

Sn - Time of Service Initiation for nth Aircraft

Delay Incurred with Gaussian Distribution about Scheduled Arrival

Figure 5.

If the arrivals were scheduled at intervals corresponding to the saturation capacity interval, then every 2nd aircraft would be delayed by 6 sigma for the condition depicted in fig 5b and the average delay would be 3 sigma. Thus, for a 1 sigma value of 5 sec the average delay, when the demand is at the saturation level, would be 15 sec. A basic, implicit assumption in this example is that the truncated 3 sigma value is less than 1/2 the service time associated with the saturation capacity.

The scheduled arrival scheme with a gaussian distribution in actual arrival about the scheduled arrival time, is considerably superior to the situation where the aircraft arrive with a Poisson distribution. In the latter case the delays bebecome extremely large as the arrival rate approaches the saturation capacity (fig 4). From a delay standpoint there would be a considerable amount of benefit, in the form of delay reduction, if the aircraft using the airport system were scheduled over the region of movement.

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