NASA Contractor Report 4248

Descent Strategy Comparisons for TNAV-Equipped Aircraft Under Airplane-Preferred Operating Conditions

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Scientific and Technical
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1989

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1.0 SUMMARY

A study was undertaken to evaluate three 4D descent strategies employed by TNAV-equipped aircraft in an advanced metering air traffic control (ATC) environment. The Flow Management Evaluation Model (FMEM) was used to assess performance using three criteria when traffic enters the simulation under preferred cruise operating conditions (altitude and speed): throughput, fuel usage, and conflict probability. In comparison to an evaluation previously performed under NASA contract, the current analysis indicates that the optimal descent strategy is preferred over the clean-idle and constant descent angle (CFPA) strategies when all three criteria are considered.

2.0 INTRODUCTION

A previous study performed by The Boeing Company examined the sensitivity of arrival traffic throughput, fuel usage, and one measure of controller workload (conflict frequency) to 4D descent strategies (ref. 1, hereafter referred to as the previous study). These strategies consisted of the clean-idle Mach/CAS, constant flight path angle (CFPA) Mach/CAS and an energy-optimal algorithm utilizing Pontryagin's Minimum Principle. The Flow Management Evaluation Model (FMEM) was used to represent air traffic operations over a common arrival route at an airport where an advanced time-based metering system based on a postulated extension of En Route Metering (ERM) would be in use. The sensitivity study assumed that all arrival traffic, represented by three Boeing airplane types (B737-300, B747-200, and B767-200), entered the simulation at a common altitude (FL 370), speed (Mach 0.78) and distance from the meter fix (200 NM). These constraints were imposed to examine the effects only of differences in descent strategy and, to a great extent, represent much more severe conditions than 4D RNAV arrival traffic might be expected to experience. Additional details of the study assumptions and methodology are contained in the reference.

The study results indicated that, for traffic mixes in which the B737-type predominated (over 70%), the optimal strategy represented the best compromise between throughput performance and fuel efficiency. If the proportion of the B747-type were increased, throughput performance decreased more rapidly with the optimal strategy than with the clean-idle or CFPA. Furthermore, in a *mixed strategy* environment, system throughput appeared to be more sensitive to the optimal than to any other.

Because of the observation that most conflicts occurred at cruise altitude due to differences in airplane-dependent speed-control delay absorption strategies, the analysis suggested that significant performance differences among descent strategies might be ameliorated by taking advantage of extra capacity available in the airspace, such as would be available if traffic arrived at different altitudes. This report examines the effect of descent strategy on traffic, consisting of the three airplane types, arriving over a common route and initially at their preferred operating altitudes and speeds, thereby providing added initial vertical separation among the three airplane types. This study is the first part of the two-part analysis defined under Task Assignment 7 of NASA contract NAS1-18027. The other part of the task evaluates 4D descent strategies in a Denver air traffic environment having

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multiple arrival routes and assuming scheduled, high-performance turbojet arrivals taken from May 1987 Official Airline Guide (OAG) data. The results of that analysis will be summarized in a separate contractor report.

3.0 SYMBOLS AND ABBREVIATIONS

ATC	air traffic control
ATOPS	Advanced Transport Operating Systems
CAS	calibrated airspeed
CFPA	constant flight path angle
$c_i(T)$	conflict counted for Ith airplane pair
$d_i(T)$	delay between airplane pair i to maintain minimum separation
D_n	total delay to maintain minimum separation
DEN	Denver Stapleton International Airport
ERM	en route metering
$\bar{F}$	average fuel usage per airplane
FAA	Federal Aviation Administration
FB_k	conflict-free fuel of the kth airplane in making its 4D time
ff_k	fuel flow of kth airplane at cruise altitude and speed
ft	feet
FL	flight level
FMEM	Flow Management Evaluation Model
F_n	total conflict-free fleet fuel
4D	four-dimensional
$g_i(T)$	maximum of initial time separation T or minimum time separation Δt_{ij}
JFK	John F. Kennedy International Airport
LAX	Los Angeles International Airport
$M(\bar{F})$	mean of fuel usage
$M(N_{con})$	mean of conflict count
$M(\bar{R})$	mean of meter fix throughput
n	number of airplane pairs
NASA	National Aeronautics and Space Administration
N_{con}	total number of conflicts
NM	nautical mile
OAG	Official Airline Guide
$\bar{R}$	average meter fix throughput
RNAV	radio navigation
T	arrival time spacing
t_d	elapsed time between meter fix crossings of first and last airplane

Δt_{ij} minimum conflict-free time separation between airplane pair ij

TNAV   time navigation

ω_{ij} probability of airplane type i followed by airplane type j at a particular airport

4.0 OBJECTIVES, ASSUMPTIONS AND METHODOLOGY

Reference 1 concluded that the optimal strategy represented the best compromise between throughput performance and fuel usage, in a traffic environment in which the B737 type predominated (over 70%). Most of the conflicts occurred because all airplane types began their descents at the same cruise altitude (FL370). Particularly, in the cruise portion of flight, an airplane of one type poses a potential conflict problem with an airplane of another type, when both use the optimal stategy, because of their different optimum cruise speeds.

The objective of this study was to investigate the hypothesis that separating arrival traffic by altitude according to airplane type decreases the sensitivities of system throughput and fuel to descent strategy type. The study is part of a continuing effort to analyze and recommend a preferred descent strategy or strategies for use by 4D RNAV-equipped airplanes in future ATC operations that will have time-based metering.

The study assumed a future ATC environment when most air carrier and other high-performance aircraft will have advanced flight management systems with time navigation (TNAV) capabilities.

4.1 DESCENT STRATEGIES

The descent strategy options evaluated for this study were the same as those examined in Reference 1: clean-idle Mach/CAS, constant flight path angle Mach/CAS, and point-mass optimal using variable speed and thrust schedules throughout the descent. These descent strategies are described in detail in Reference 1.

4.2 AIRPLANE ASSUMPTIONS

Assumptions were made to equate all commercial turbojet airplane types to three Boeing types: the B737-300, B767-200, and B747-200. The equivalents are summarized in Table 1.

Table 1. Airplane Equivalents

Airplane model	Boeing equivalent
DC-9/MD80	
B727	
B737	B737-300
BAC-111	
BAC-146	
B707	
DC-8	
A-300	B767-200
A-310	
B757	
B767	
DC-10/MD11	
L-1011	B747-200
B747	

Some substitutions were justified on the basis that older airplane types will most likely be replaced by their modern equivalents by the year 1995. These three types were also considered to run the gamut of turbojet aircraft weights and performance. Two weight categories ("light" and "heavy") have been assigned to each airplane type to diversify airplane performance even further. The selection of the weight range was made for the previous sensitivity study described in Reference 1 and was dictated by two considerations: (1) a realistic range of approach weights and (2) a parametric compromise between maximum weight range and maximum delay margin. The performance characteristics of the B737-300 (CFM56-3-B1 engines), B767-200 (JT9D-7R4D engines), and B747-200 (RB-211B engines) were modeled.

The same weight ranges were assumed for this study. However, each airplane type was assumed to operate at its preferred cruise altitude and speed. For each type, the altitudes and speeds depend on weight. The conditions assumed for this study are shown in Table 2.

Table 2. Assumed Operating Conditions by Airplane Type and Weight

Type	Weight (lb)	Altitude (ft)	Speed (Mach)
B737	90000	35000	0.745
B737	100000	35000	0.745
B747	475000	41000	0.820
B747	564000	37000	0.820
B767	210000	37000	0.795
B767	270000	37000	0.795

4.3 TRAFFIC MIXES

As in the previous study, a composite U.S. fleet mix, represented by the three Boeing airplane types, for the 1995 time period was assumed. This mix was based on extrapolations of current traffic trends at Denver Stapleton (DEN), John F. Kennedy (JFK), and Los Angeles (LAX) international airports, as well as one with a typical ERM traffic mix. The typical ERM distribution was computed as the average of arrival mixtures at three ERM airports: Denver Stapleton, Dallas-Fort Worth, and Minneapolis-St. Paul. The distributions by airplane type are listed in Table 3. Table 3 shows that the B737 aircraft type constitutes only 42.6% of all arrivals at JFK because of offloading of short-haul operations to nearby municipal airports.

4.4 ATC CLEARANCES AND THE FREEZE TIME

The FMEM simulates arrival traffic operations at an airport participating in the ERM program. The model had been specifically configured to represent the Denver Air Route Traffic Control Center (ARTCC) airspace and arrival operations at Denver Stapleton

Table 3. Airport Arrival Distributions by Airplane Type (Percent)

Airport	Airplane Type		
	B737-300	B767-200	B747-200
John F. Kennedy	42.6	11.5	45.9
Los Angeles	67.9	6.2	25.9
Denver Stapleton	86.2	7.8	6.0
Typical ERM	87.9	4.8	7.3

Data derived from *Airport Activity Statistics of Certificated Route Air Carriers*, Office of Management Systems (Federal Aviation Administration) and Office of Aviation Information Management (Research and Special Programs Administration), December 1984.

International Airport. With a slight modification, the FMEM was made independent of a particular airspace structure for the purposes of this and the previous sensitivity study. By assuming that all traffic arrive over the same arrival route, a more stringent traffic environment is constructed than if traffic were dispersed over an entire airspace. A complete description of the FMEM is contained in Reference 2. Descriptions of its capabilities that are pertinent to the current analysis follow.

Airplanes are assigned landing slots based on a first-come, first-served mechanization and the minimum time separation interval, known as the airplane arrival interval (AAI). The resultant schedule determines required meter fix times for all arrival traffic. ERM guarantees, or "freezes," an airplane's landing time when it is within a fixed number of flying minutes from its expected meter fix arrival time. This fixed number of minutes is called the *freeze calculated landing time* (FCLT) parameter. A TNAV-equipped airplane is presumed to be given its meter fix time assignment by air traffic control when it enters the freeze region at its freeze time. The difference between the airplane's assigned meter fix time and its freeze time is its required 4D time, which the airplane must absorb to make good its meter fix time. The assignment process is a dynamic one and can produce varying delay requirements on the traffic, depending on demand.

4.5 DESCENT TIME REQUIREMENT

Again, in Reference 1, the 4D descent time of 1739 seconds was selected because, for all three airplane types, it lies within all their speed envelopes, when they all shared common initial conditions (cruise altitude and speed and initial range of 200 NM) and used the clean-idle and CFPA strategies. The optimal strategy was assumed not to produce the constraining descent times because that strategy which is not limited to a Mach/CAS speed schedule, makes greater use of its performance envelope.

Table 4 lists the high- and low-speed (Mach/CAS) descent times for all combinations of airplane types, two weight categories, and two descent strategies. It should be noted that these times still permit the use of the descent time requirement of 1739 seconds.

Table 4 . High- and Low-Speed Descent Times, Clean-Idle and CFPA Strategies

Type	Weight (lb)	Strategy	Descent time (sec)	
			Low	High
B737	90000	Clean-idle	1497	1851
B737	90000	CFPA	1499	1865
B737	100000	Clean-idle	1530	1854
B737	100000	CFPA	1535	1865
B747	475000	Clean-idle	1486	1769
B747	475000	CFPA	1496	1763
B747	564000	Clean-idle	1478	1799
B747	564000	CFPA	1482	1789
B767	210000	Clean-idle	1546	2000
B767	210000	CFPA	1545	1984
B767	270000	Clean-idle	1551	2005
B767	270000	CFPA	1549	1984

5.0 SENSITIVITY ANALYSIS

The following analysis parametrically varies arrival rate (as measured at cruise altitude entry points) and computes throughput (meter fix arrival rate), fuel usage and conflict workload. Any vectors required to eliminate conflicts are taken at cruise altitude as soon as traffic enters the simulation. The need for such vectoring maneuvers will increase as the arrival rate is increased. The individual airplane's additional fuel usage will be proportional to the airplane's excess delay.

Throughput, fuel usage, and conflict workload performance were averaged over 1000 runs for each of the three descent strategies using randomly generated traffic lists consisting of 121 airplanes (120 pairs) each. Each list was subject to the constraint that it satisfy the airport mix of the three Boeing airplane types (Table 3). A 4D required time of 1739 seconds was used in order to be consistent with the previous study.

If Δt_i can be viewed as the minimum time separation between airplane pair i that is required to maintain nonconflicting separation between that pair, then the trail airplane will need delay of magnitude (Δt_i - T) when input arrival spacing T is less than Δt_i. That is, the trail airplane of pair i must take additional delay (Δt_i - T) when initial spacing is insufficient to maintain minimum time separation needed to resolve conflict. In the context of this study, T is the time interval between the entry point times of two successive arrivals. The excess delay is arbitrarily assumed to be taken by the trail airplane at its original cruise altitude and speed immediately after receiving its 4D clearance. For this reason, the only airplane pairs that will be affected are those initially at the same cruise altitude. As can be seen, conflict frequency is expected to decline relative to results obtained in the analysis described in Reference 1.

5.1 CONFLICT-INDUCED DELAYS

If input traffic of arbitrary sequence of airplane types consists of n airplane pairs, then total delay attributed to maintaining proper separation, D_n, can be written as

$$D_n = d_1(T) + \left[d_1(T) + d_2(T)\right] + ... + \left[d_1(T) + ... + d_n(T)\right] \qquad (1)$$

where D_n = total delay for minimum separation among n airplane pairs

T = arrival spacing between airplane pairs

$$d_i(T) = \begin{cases} 0 & when \ \Delta t_i \leq T \\ \\ \Delta t_i - T & when \ \Delta t_i > T \end{cases} \tag{2}$$

Note that the term $\Delta t_i - T$ is the delay that the trail airplane of pair i is required to take when initial spacing (input spacing time) is insufficient to maintain minimum time separation needed to relieve conflict between the pair, and that for any given delay required of pair i, the same delay has to be taken by all subsequent pairs through pair n to satisfy the same conflict-free criterion. This cascading phenomenon causes delay penalties for aircraft appearing later in the traffic list.

5.2 FUEL USAGE

The total fuel used by the fleet, F_n, is given by the equation:

$$F_n = FB_1 + \left[FB_2 + ff_2 d_1(T) \right] + ... + \left\{ FB_{n+1} + ff_{n+1} \left[d_1(T) + ... + d_n(T) \right] \right\} \tag{3}$$

where FB_k = conflict-free fuel used by the kth airplane in making its 4D time

ff_k = fuel flow of kth airplane at cruise altitude and speed

and $d_i(T)$ is given by (2).

Total fuel is shown to depend on total accumulated delays of all n airplane pairs.

Average fuel usage per airplane is

$$F = \frac{F_n}{n+1}$$

5.3 SYSTEM THROUGHPUT

For n airplane pairs, average meter fix throughput, $\bar{R}$, is given by

$$\bar{R} = \frac{n}{t_{el}} \tag{5}$$

where t_{el} is the elapsed time between the meter fix crossings of the first and last airplanes in the traffic.

In turn,

$$t_{el} = \sum_{i=1}^{n} g_i(T) \tag{6}$$

where

$$g_i(T) = \begin{cases} T & when \ \Delta t_i \leq T \\ \Delta t_i & when \ \Delta t_i > T \end{cases} \tag{7}$$

The term $g_i(T)$ is either the interarrival spacing or the spacing required to maintain separation between airplane pair i. When no delay is created by any airplane pair, equation (5) implies that average throughput is $1/T$. Moreover, as conflict-avoiding delays are created, throughput can no longer match arrival rate. In particular, t_{el} decreases hyperbolically with increasing arrival rate until the first applicable airplane pair(s)

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comes into conflict. When all sequential pairs are in conflict, throughput no longer depends on arrival spacing T, but only on conflict-avoiding time separations.

$$\bar{R} = \frac{n}{\sum_{i=1}^{n} \Delta t_i} \tag{8}$$

Therefore, throughput reaches saturation (becomes constant); system delay on the other hand increases according to equation (1).

5.4 CONFLICT WORKLOAD

One measure of controller workload is the number of clearances required to be issued to resolve conflicts (maintain minimum separation). This can be translated to the number of trail airplanes among n pairs that require vectors for a particular arrival rate. Conflict count N_{con} is therefore:

$$N_{con} = \sum_{i=1}^{n} c_i(T) \tag{9}$$

where

$$c_i(T) = \begin{cases} 0 & when \ \Delta t_i \leq T \\ 1 & when \ \Delta t_i > T \end{cases} \tag{10}$$

5.5 SAMPLE PERFORMANCE MEANS

If equations (4), (5) and (10) are averaged over a large number of samples, m, using randomly generated traffic inputs, provided that each input is constrained to the airplane-

type mixes applicable to a particular airport, then a good estimate of the throughput, fuel usage, and conflict workload means might be obtained. Statistically, the actual mean can be closely approximated when m is made arbitrarily large, so that

$$M(\bar{R}) = \lim_{m \to \infty} \frac{1}{m} \sum_{k=1}^{m} (\bar{R})_k = n \lim_{m \to \infty} \frac{1}{m} \sum_{k=1}^{m} \left(\frac{1}{t_d} \right)_k \tag{11}$$

$$M(\bar{F}) = \lim_{m \to \infty} \frac{1}{m} \sum_{k=1}^{m} (\bar{F})_k = \frac{1}{n+1} \lim_{m \to \infty} \frac{1}{m} \sum_{k=1}^{m} (F_n)_k \tag{12}$$

$$M(N_{con}) = \lim_{m \to \infty} \frac{1}{m} \sum_{k=1}^{m} (N_{con})_k = \lim_{m \to \infty} \frac{1}{m} \sum_{k=1}^{m} \sum_{i=1}^{n} c_i(T) \tag{13}$$

where k refers to one sample and n is the number of airplane pairs.

Normalizing expected conflict count [equation (13)] by n, the total number of airplane pairs potentially susceptible to conflict, is the probability that conflict occurs. In this study, n represents the number of sequential pairs at the meter fix.

$$P(conflict) = \frac{1}{n} M(N_{con}) \tag{14}$$

Although conflict probability (susceptibility) is related to conflict count, it is a more useful system performance concept, while also preserving the notion of controller workload.

6.0 RESULTS

Throughput performance is shown in Figures 1 through 4 for airports with JFK, LAX, Denver, and typical ERM traffic mixes. The plots are based on equations (11) and (8) for $m = 1000$, assuming randomly generated 121-airplane traffic sequences, each adhering to appropriate airplane-type distributions. After an input arrival rate of 57.77 airplanes per hour, throughput reaches saturation for all airport mixes (indeed, for any mix). Maximum throughputs in general are comparable, with the optimal strategy having a small advantage over the clean-idle and CFPA strategies.

At low arrival rates (when no conflicts occur), the ranking of average fuel performance is as expected, with the optimal using the least fuel and the CFPA the most, as depicted in Figures 5 through 8. The fuel curves are plots of equation (12) for $m = 1000$. As arrival rate increases and produces conflicts, unlike the behavior in the previous study, the fuel advantage of the optimal strategy is maintained, even well beyond the arrival rate producing saturation (57.77 ACPH). This characteristic is true for all traffic mixes.

Conflict probability for a range of arrival rates are shown in Figures 9 through 12, which reflect controller workload, as measured by conflict count. These data are based on equation (14) for $m = 1000$. The data show that the CFPA strategy generates the most conflicts at the lowest arrival rates (approximately 36-50 ACPH). Furthermore, after an arrival rate of 57.77 ACPH, all airplanes will be involved in conflict, regardless of strategy and traffic mix.
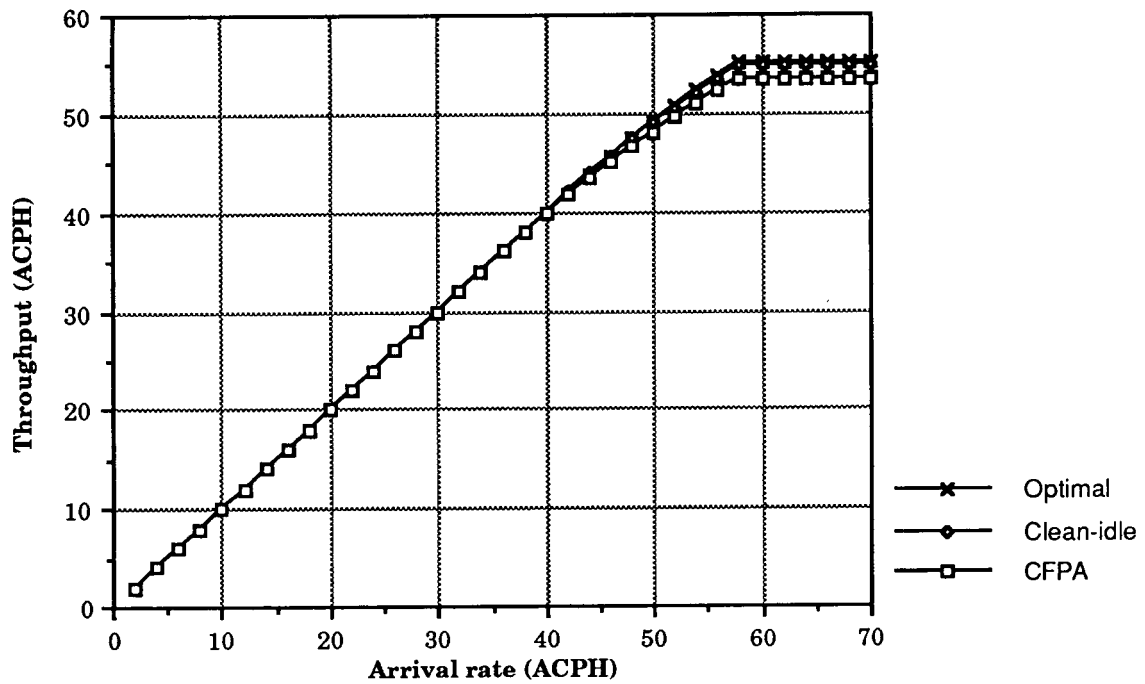
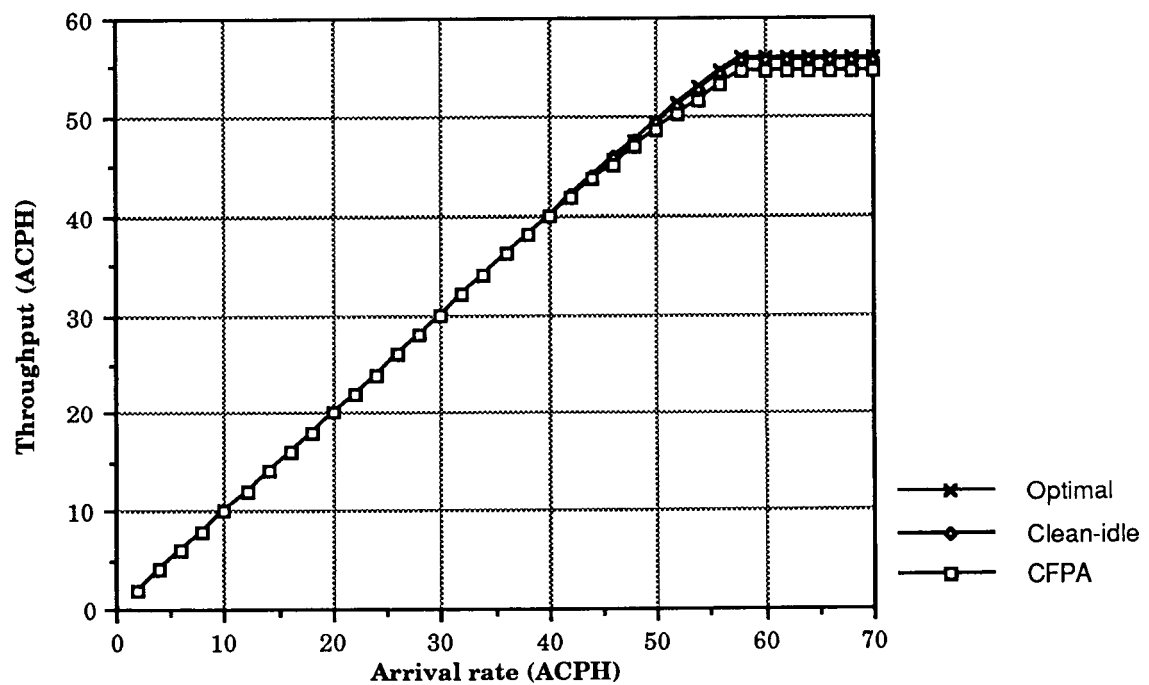**Figure 1. Comparative Throughput, JFK Mix, 1739-Second Elapsed Time**

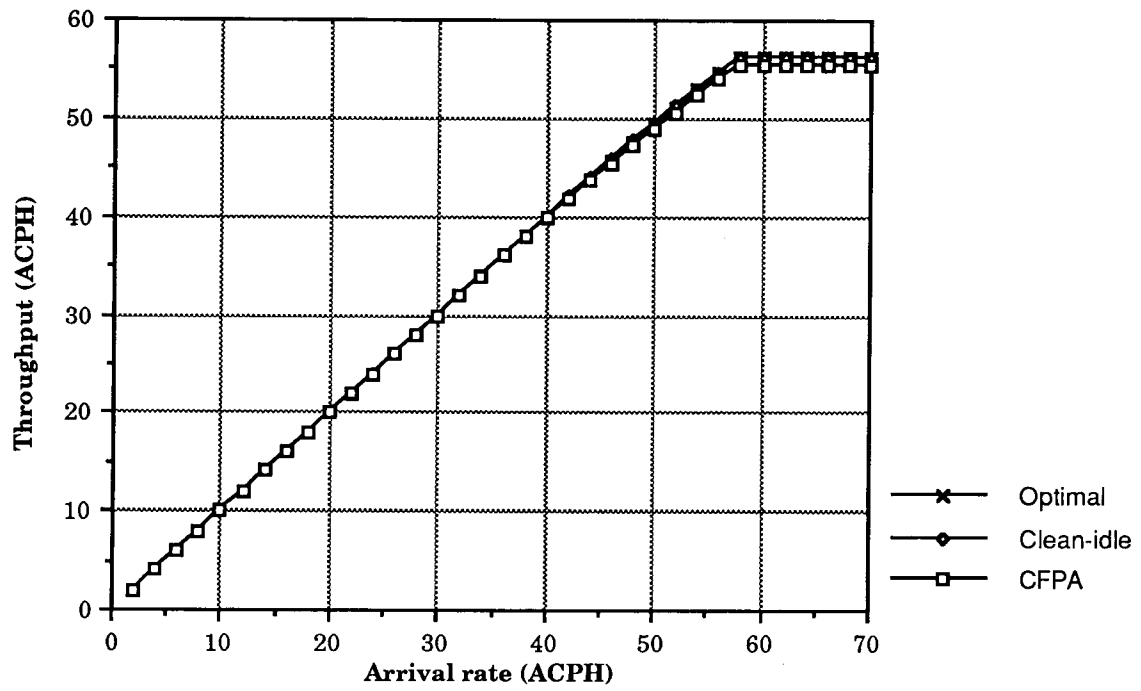**Figure 2. Comparative Throughput, LAX Mix, 1739-Second Elapsed Time**

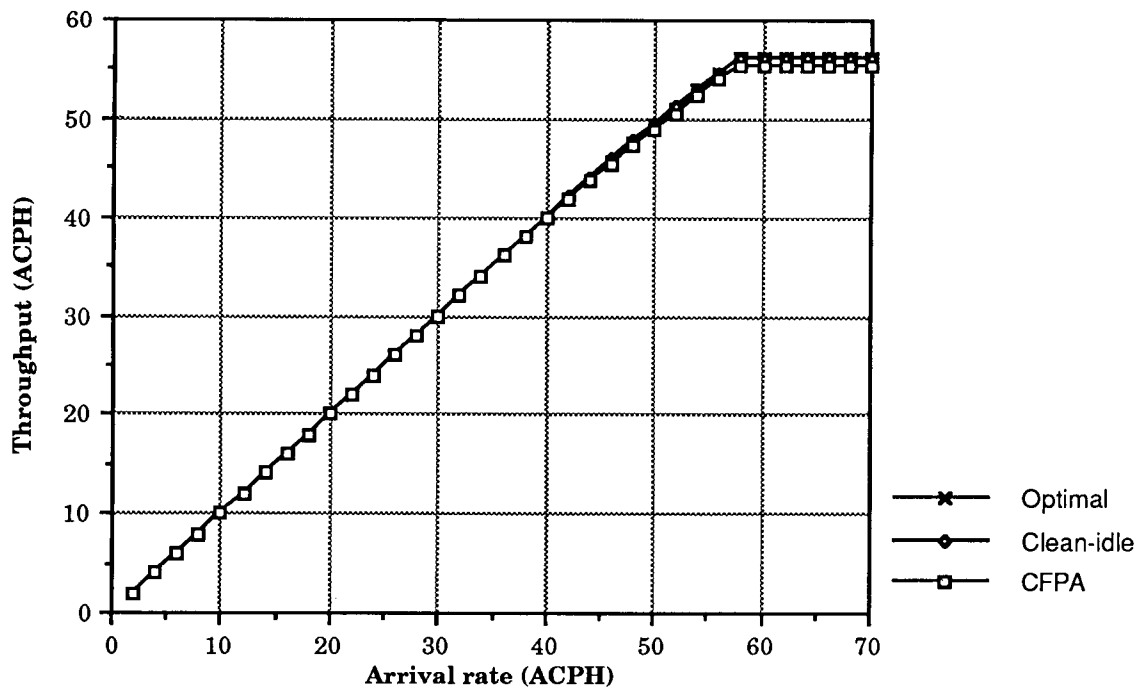**Figure 3. Comparative Throughput, Denver Mix, 1739-Second Elapsed Time**

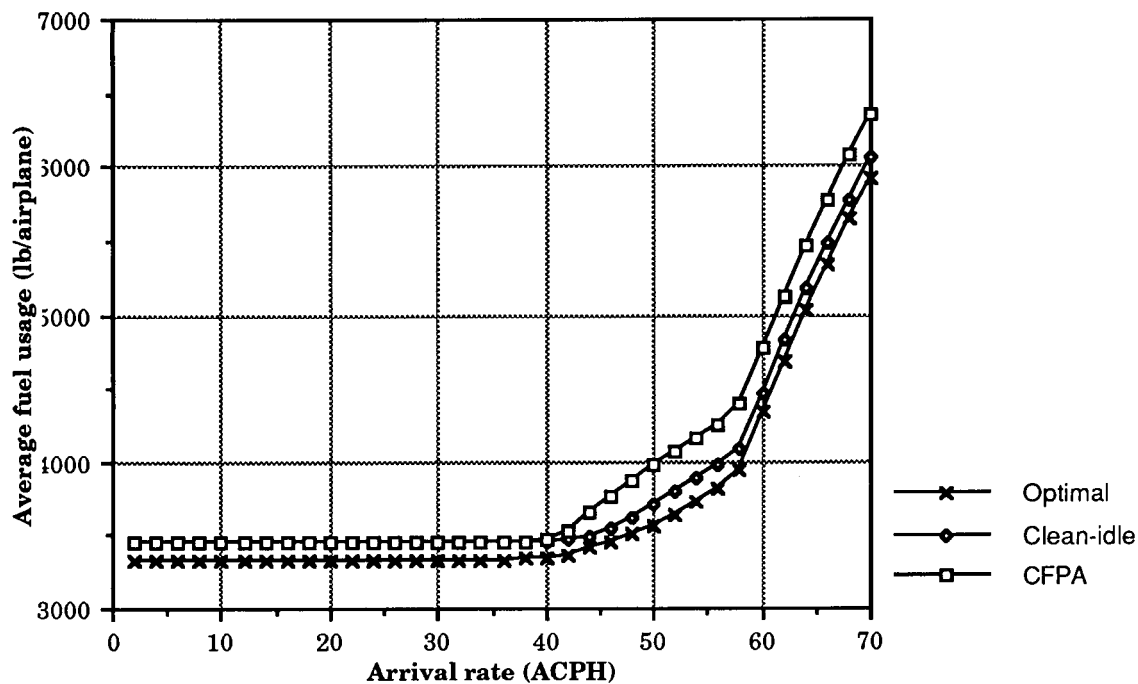**Figure 4. Comparative Throughput, ERM Mix, 1739-Second Elapsed Time**

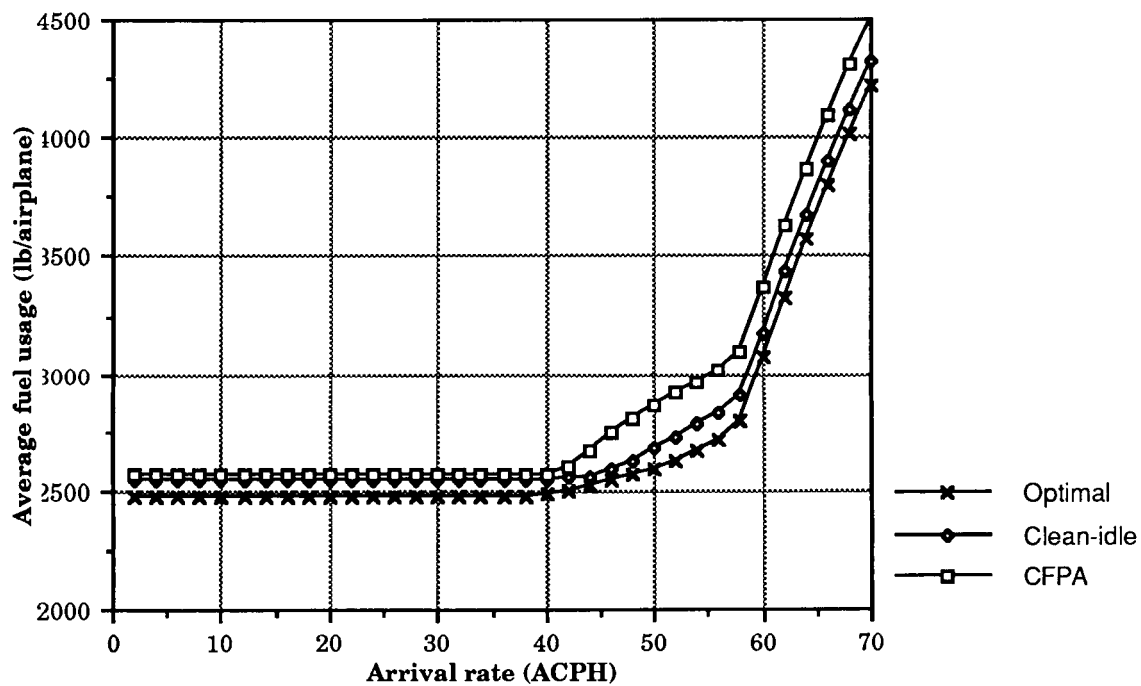**Figure 5. Comparative Fuel Usage, JFK Mix, 1739-Second Elapsed Time**

Figure 6. Comparative Fuel Usage, LAX Mix, 1739-Second Elapsed Time
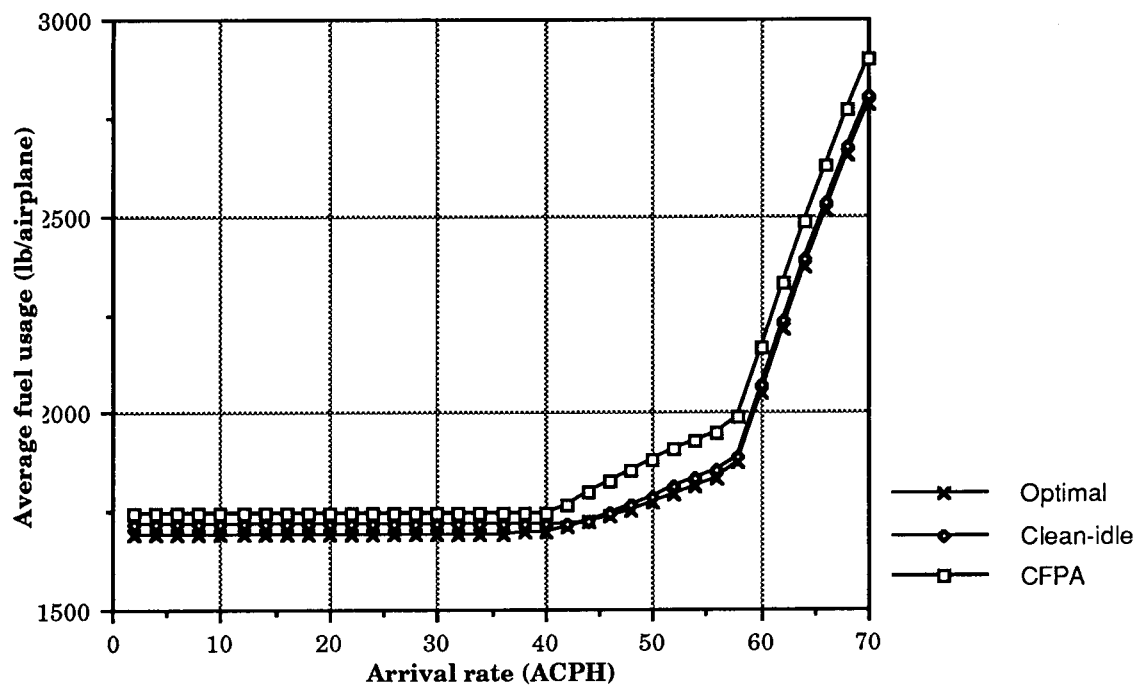
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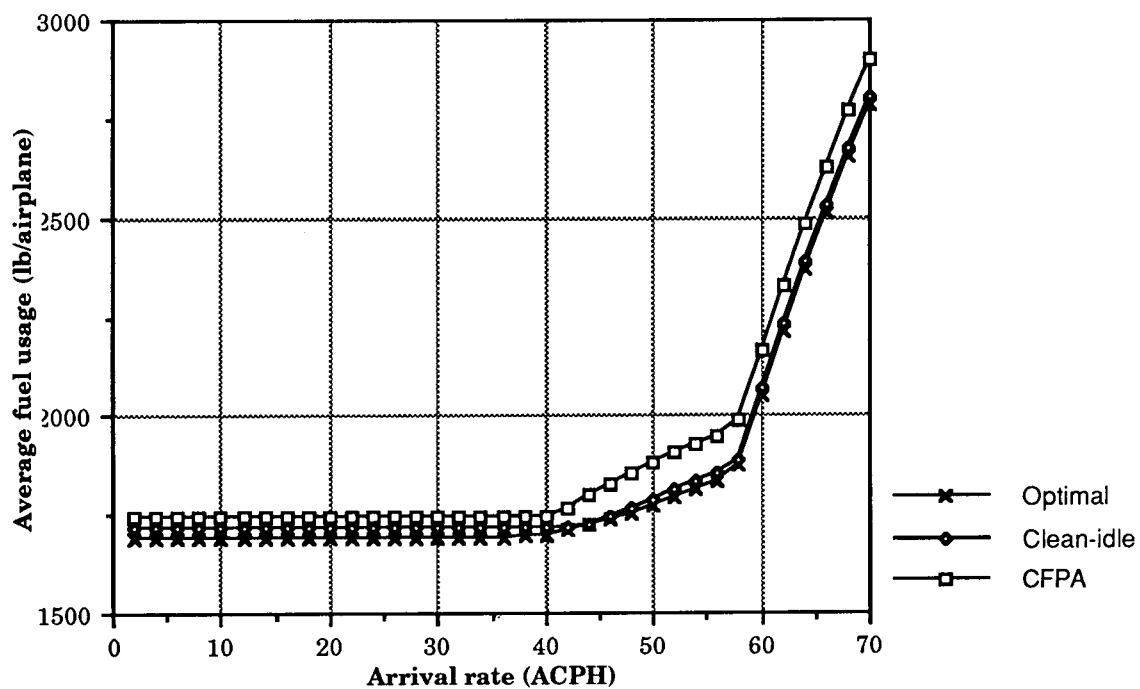**Figure 7. Comparative Fuel Usage, Denver Mix, 1739-Second Elapsed Time**

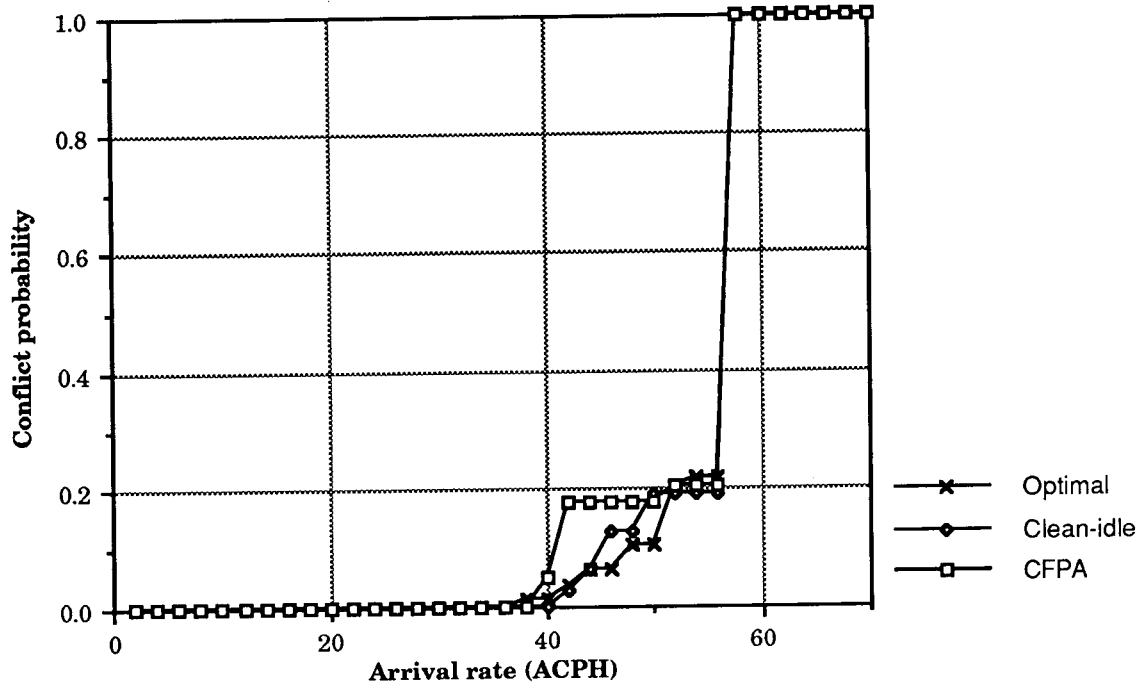**Figure 8. Comparative Fuel Usage, ERM Mix, 1739-Second Elapsed Time**

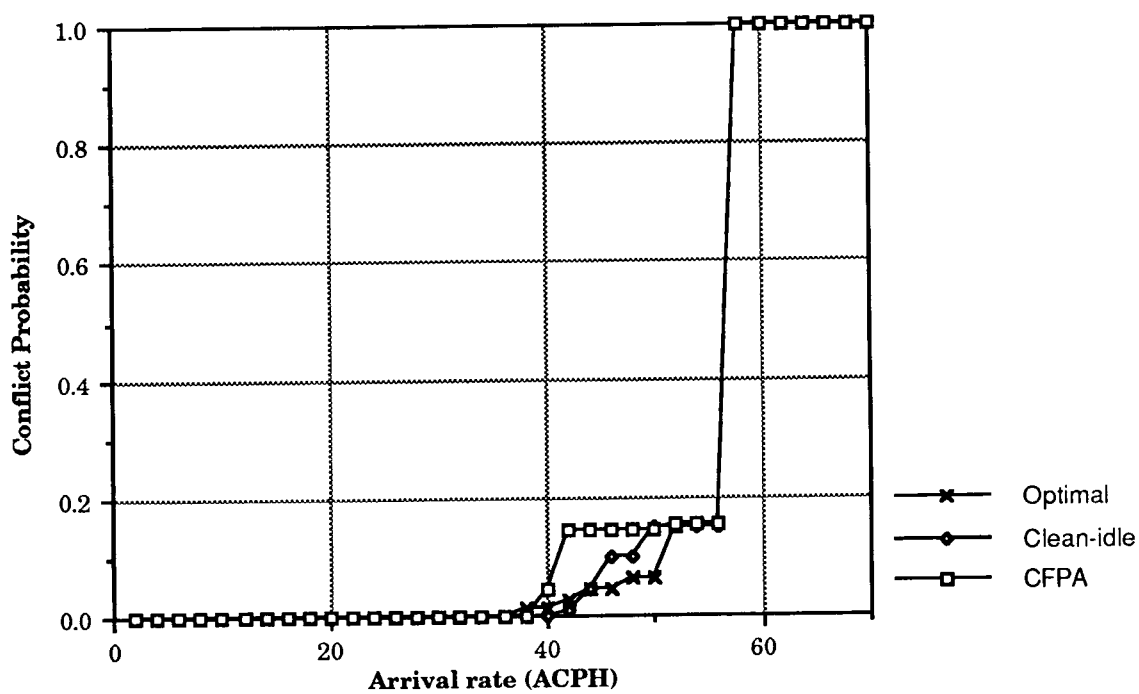**Figure 9. Comparative Conflict Probability, JFK Mix, 1739-Second Elapsed Time**

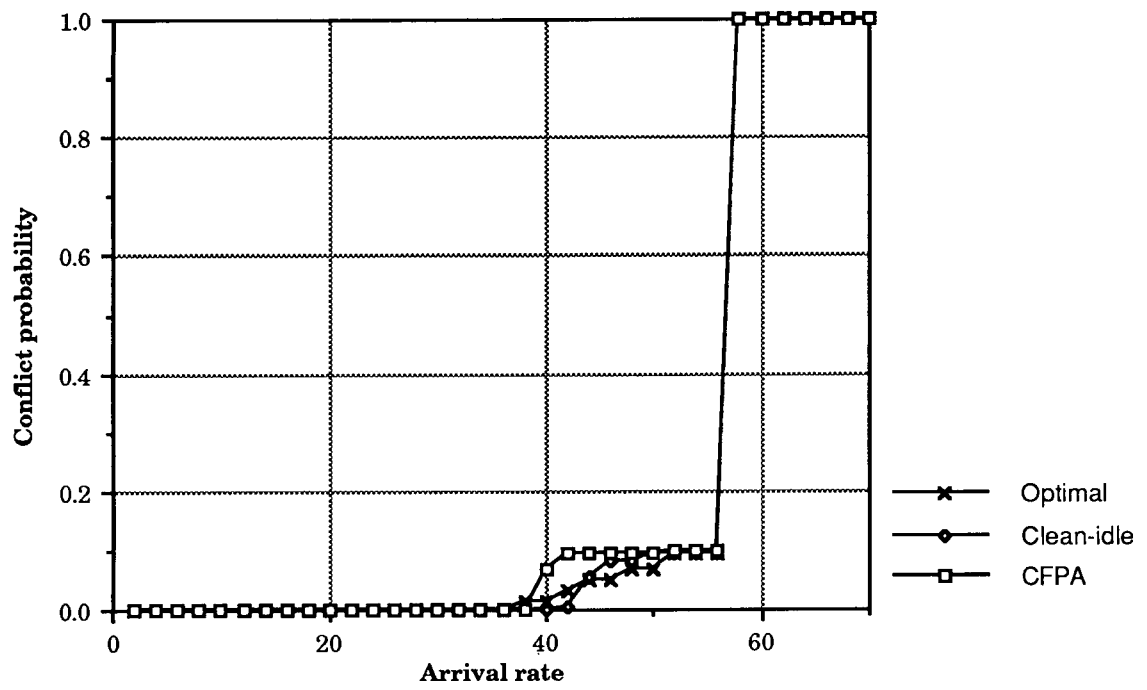**Figure 10. Comparative Conflict Probability, LAX Mix, 1739-Second Elapsed Time**

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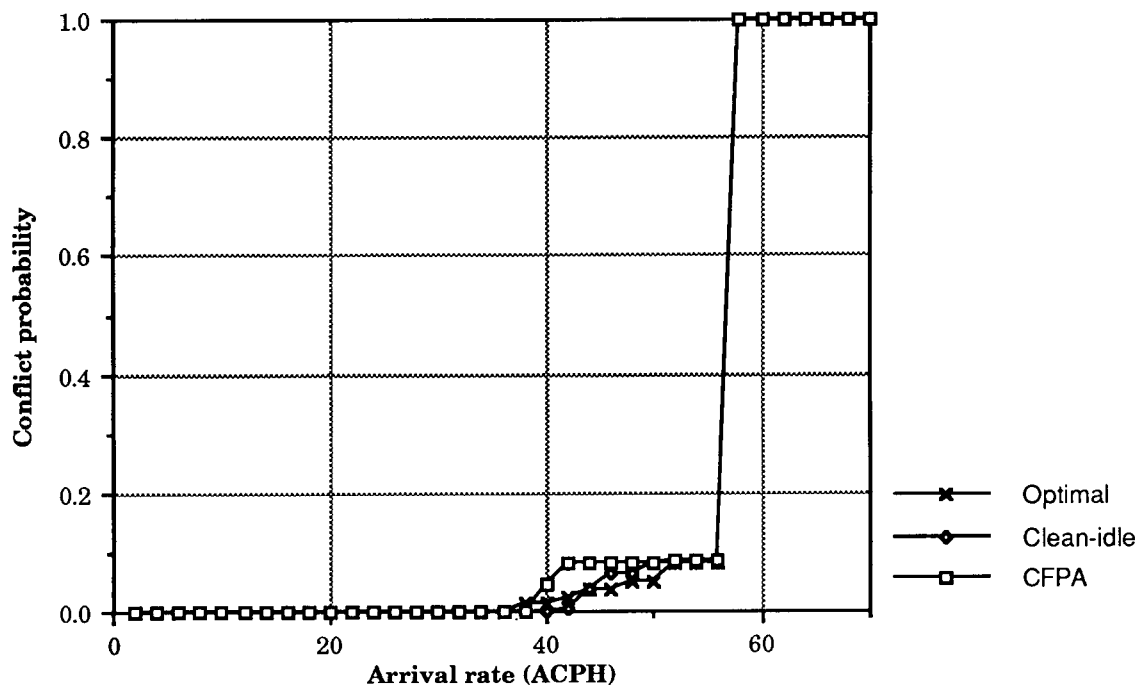**Figure 11. Comparative Conflict Probability, DEN Mix, 1739-Second Elapsed Time**

Figure 12. Comparative Conflict Probability, ERM Mix, 1739-Second Elapsed Time

7.0 ANALYSIS

For the purposes of comparison, differences in throughput, fuel usage and conflict performance between this and the previous studies, labeled the *best cruise* and *common cruise* conditions, respectively, for only ERM and JFK traffic mixes are calculated. These mixes represent two extremes of traffic distributions at airports where ERM has been operational. Figures 13 through 18 quantify the differences between the results of best and common cruise conditions for the ERM and JFK traffic mixes.

7.1 THROUGHPUT PERFORMANCE

Best cruise throughput gains (in percent) relative to common cruise conditions are depicted in Figures 13 and 14. Fuel usage of the best cruise cases in relation to common cruise conditions are shown in Figures 15 and 16. Finally, conflict sensitivity differences between the two study assumptions are illustrated in Figures 17 and 18.
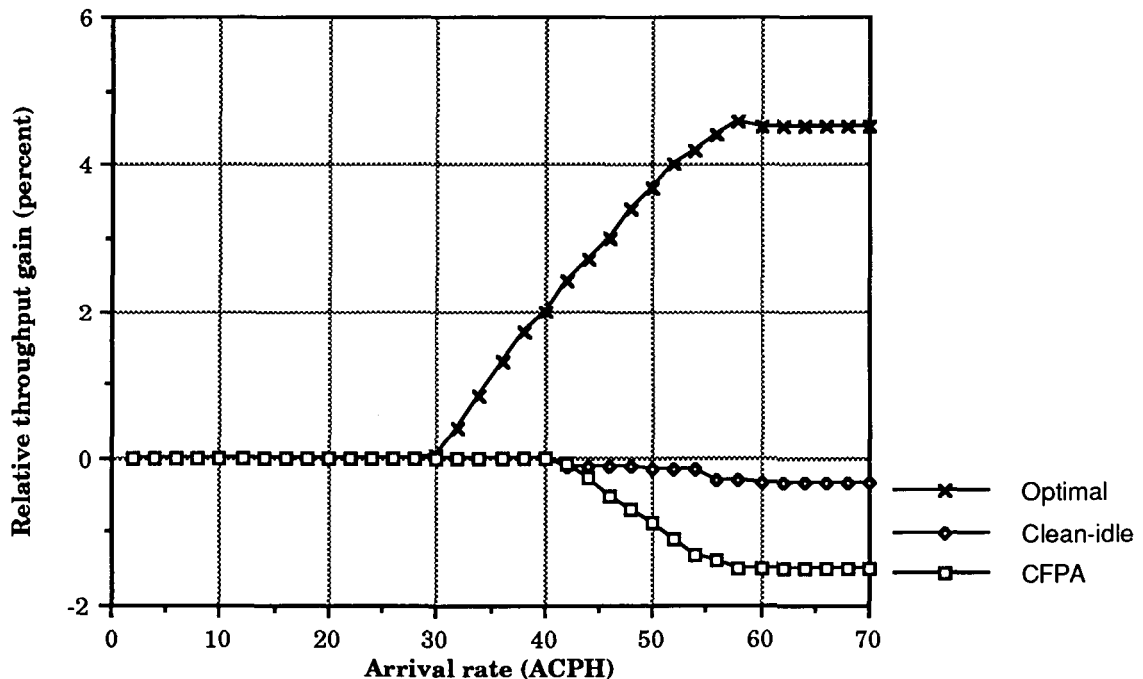
Figure 13. Throughput Gain Relative to Common Cruise Conditions, ERM Mix, 1739-Second Elapsed Time
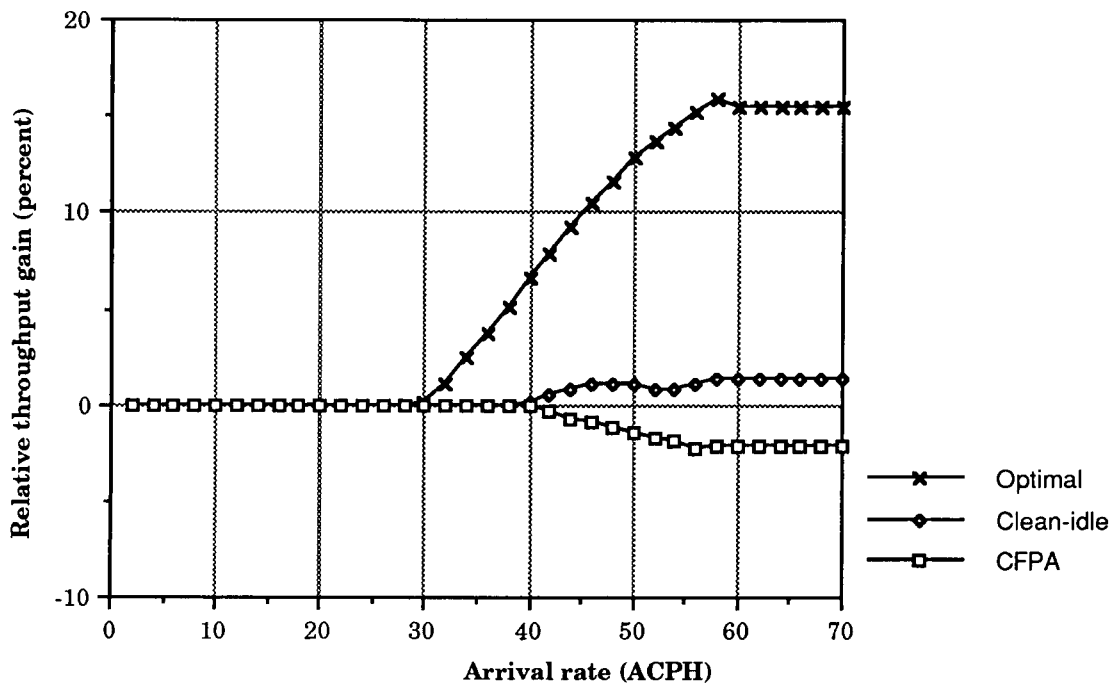
Figure 14. Throughput Gain Relative to Common Cruise Conditions, JFK Mix, 1739-Second Elapsed Time

Throughput performance, as represented by equation (5), is a function of traffic arrival rate and minimum time separations. For a given airplane-type mix and arrival rate, differences in throughput between best cruise and common cruise conditions depend only on the respective minimum time separations. Maximum throughputs (JFK and ERM mixes) for all three strategies are compared in Table 5. Saturation (maximum throughput) occurs when all sequential pairs conflict. After an input rate that initially causes saturation, increasing the arrival rate only increases delay required to maintain minimum separation [equation (1)].

Table 5. Maximum Throughputs for JFK and ERM Mixes

Airplane mix	Strategy	Best cruise	Common Cruise	Gain (%)
JFK	Optimal	55.05	47.61	15.6
	CFPA	53.64	54.76	-2.0
	Clean-idle	54.89	54.12	1.4
ERM	Optimal	56.46	54.04	4.5
	CFPA	55.79	56.65	-1.5
	Clean-idle	56.65	56.83	-0.3

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The throughput plots indicate that the optimal strategy conflict performance improved dramatically when traffic is altitude-segregated by airplane type rather than all aircraft arriving at a common altitude. At saturation, the optimal strategy throughput improvements are 4.5 and 15 percent for ERM and JFK mixes, respectively. CFPA throughput performance degraded slightly (1.5 and 2 percent) for the ERM and JFK mixes, respectively. The clean-idle strategy experienced a slight decrease for the ERM mix (0.3 percent) and a slight improvement at saturation for the JFK mix (1.4 percent).

For the purposes of comparative evaluation, the optimal strategy is judged the only strategy to have made a significant change in throughput performance. Under common cruise conditions, throughput rate at the meter fix was primarily degraded by the conflicts produced at cruise altitude (FL370) by pairs consisting of a B737 type followed by a B747 type, because of the large interarrival separation times needed to guarantee against conflicts. Degradation is more pronounced for a JFK mix where the distributions are about equal between the two airplane types. Therefore, as a result of separating airplane types by preferred altitude, the optimal strategy's throughput performance is raised to a level equivalent to those of the other two strategies.

7.2 FUEL PERFORMANCE

Figures 15 and 16 illustrate the additional fuel used by traffic consisting of ERM and JFK mixes under best cruise conditions relative to common cruise conditions. These data can be analyzed in relation to Figures 5 and 8, which show best-cruise total fuel usage for the two airport mixes.
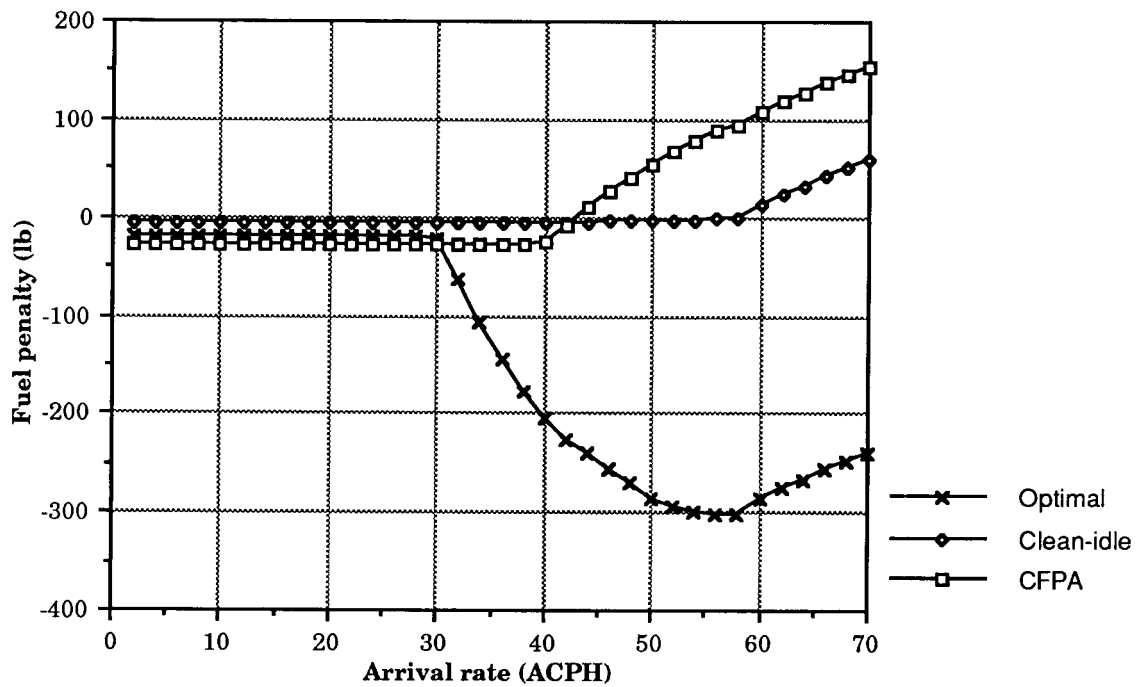
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Figure 15. Fuel Usage Relative to Common Cruise Conditions, ERM Mix, 1739-Second Elapsed Time
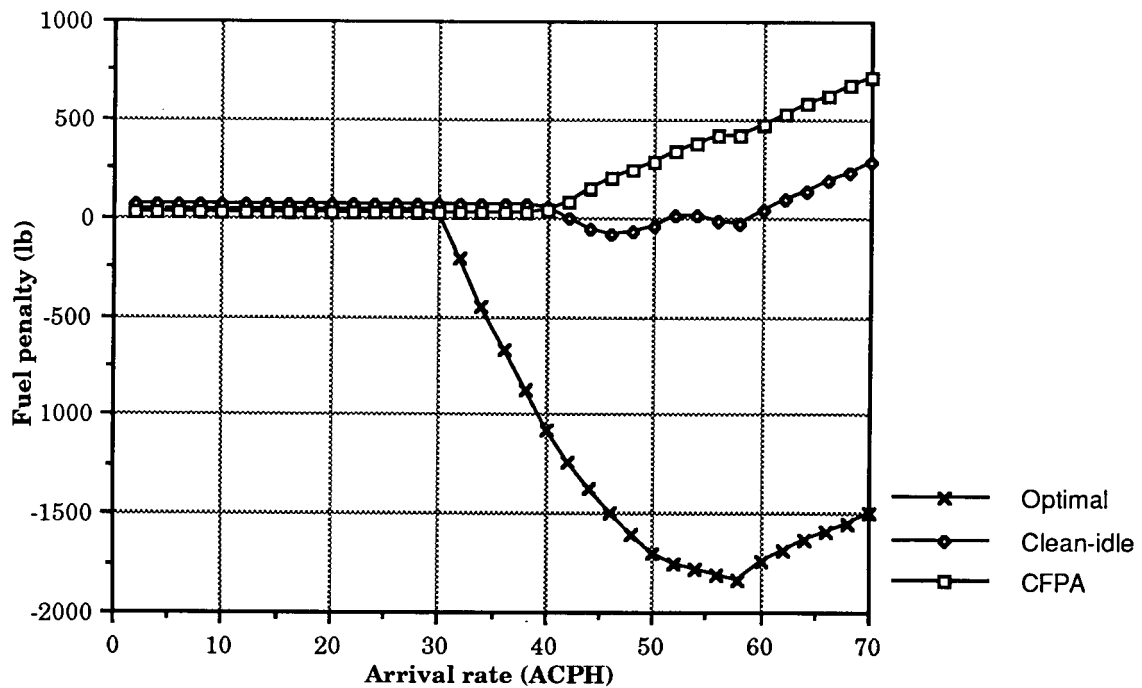

Figure 16. Fuel Usage Relative to Common Cruise Conditions, JFK Mix, 1739-Second Elapsed Time

The fuel penalty of starting traffic at best cruise conditions instead of common cruise conditions can be analyzed by solving for fuel usage differences from equation (3). Therefore,

$$\Delta F_n = \left(F_n \right)_{bc} - \left(F_n \right)_{cc} \qquad (15)$$

where bc and cc refer to best cruise and common cruise conditions, respectively. When arrival rate AR is low enough that no conflict occurs between any two airplanes in sequence among n total sequential pairs, the following is obtained from equations (3) and (15):

$$\Delta F_n = FB_{1,bc} + FB_{2,bc} + \ldots + FB_{n+1,bc} - FB_{1,cc} - FB_{2,cc} - \ldots - FB_{n+1,cc}$$

$$\Delta F_n = \sum_{i=1}^{n} \left(\Delta FB \right)_i \qquad (16)$$

where

$$\left(\Delta FB \right)_i = FB_{i,bc} - FB_{i,cc}$$

This relationship holds through a range from the lowest arrival rates up to (but not including) a threshold rate high enough to induce the first conflict. For the optimal strategy, that arrival rate threshold occurs at about 30 ACPH, while for the clean-idle and CFPA strategies, that point happens around 40 ACPH. It should be noted that in the aggregate, less fuel per airplane is used under *best cruise conditions* for an ERM mixture, while more is used for a JFK mixture, regardless of descent strategy. This is explained by two phenomena. Firstly, an ERM mix is a highly skewed distribution consisting of many more B737 types (87.9 percent of total traffic in Table 3) than B747 types (7.3 percent), while a JFK mix has a more balanced distribution between those two types (42.6 percent B737, 45.9 percent B747). Secondly, and more significantly, because of the higher initial cruise speeds of the B747 type assumed for this study (0.82 Mach, as opposed to 0.78 Mach used in the common-cruise study), the conflict-free descent fuel usage is greater. The additional fact that there are over twice as many B767 types for JFK as for ERM and that their descent fuel usage is also higher under best cruise conditions, because of higher initial cruise speed, also contributes to the higher JFK aggregate fuel.

After reaching saturation (around 57.8 ACPH arrival rate), for *every* sequential pair the arrival time separation $T = 1/AR$ is insufficient to maintain minimum separation throughout that pair's respective descents. Therefore, as discussed in paragraph 5.1, for any particular sequence of $n + 1$ airplanes, the ith airplane [which occupies the trail position of the $(i - 1)$th pair] must take $(\Delta t_{i-1} - T)$ extra time delay to maintain minimum separation. All subsequent airplanes through airplane $n + 1$ must also take delay $(\Delta t_{i-1} - T)$ as well as their own separation-maintaining delays. Hence:

$$\Delta F_n = FB_{1,bc} + \left[FB_{2,bc} + ff_{2,bc}(\Delta t_{1,bc} - T) \right]$$

$$+ \ldots + \left\{ FB_{n+1,bc} + ff_{n+1,bc} \left[\sum_{j=1}^{n} \Delta t_{j,bc} + nT \right] \right\}$$

$$- FB_{1,cc} - \left[FB_{2,cc} + ff_{2,cc}(\Delta t_{1,cc} - T) \right]$$

$$- \ldots - \left\{ FB_{n+1,cc} + ff_{n+1,cc} \left[\sum_{j=1}^{n} \Delta t_{j,cc} + nT \right] \right\}$$

$$= \sum_{i=1}^{n+1} \Delta FB_i + ff_{2,bc}(\Delta t_{1,bc} - T) - ff_{2,cc}(\Delta t_{1,cc} - T) + \ldots$$

$$+ ff_{n+1,bc} \left[\sum_{j=1}^{n} \Delta t_{j,bc} + nT \right] - ff_{n+1,cc} \left[\sum_{j=1}^{n} \Delta t_{j,cc} + nT \right]$$

$$= \sum_{i=1}^{n+1} \Delta FB_i + (ff_{2,bc}\Delta t_{1,bc} - ff_{2,cc}\Delta t_{1,cc}) - T(ff_{2,bc} - ff_{2,cc}) + \ldots$$

$$+ \left(ff_{n+1,bc} \sum_{j=1}^{n} \Delta t_{j,bc} - ff_{n+1,cc} \sum_{j=1}^{n} \Delta t_{j,cc} \right) + \left[nT(ff_{n+1,bc} - ff_{n+1,cc}) \right]$$

$$= bias\ term - \left[\Delta ff_2 T + \ldots + nT\ \Delta ff_{n+1} \right]$$

$$\Delta F_n = bias\ term - \frac{1}{AR} \sum_{m=2}^{n+1} (m-1) \Delta ff_m \tag{17}$$

where

$$bias\ term = \sum_{i=1}^{n+1} \Delta FB_i + (ff_{2,bc} \Delta t_{1,bc} - ff_{2,cc} \Delta t_{1,cc}) + \dots$$

$$+ \left(ff_{n+1,bc} \sum_{j=1}^{n} \Delta t_{j,bc} - ff_{n+1,cc} \sum_{j=1}^{n} \Delta t_{j,cc} \right)$$

$$= \sum_{i=1}^{n+1} \Delta FB_i + \sum_{m=2}^{n+1} \left(ff_{m,bc} \sum_{k=1}^{m} \Delta t_{k,bc} - ff_{m,cc} \sum_{k=1}^{m} \Delta t_{k,cc} \right) \tag{18}$$

Since all terms in equation (7.2.4) and all but arrival rate AR in equation (17) are constants, fuel usage difference varies hyperbolically with AR. The results of equations (16) and (18) are apparent in Figures 15 and 16.

Fuel difference behavior between the extremes represented by equations (16) and (18) (that is, between no delay and saturation) is characterized by the effect of cumulative delays with increasing arrival rate as ever more pairs come into conflict.

The optimal strategy benefits the most from traffic separation by airplane type. Its fuel performance under common cruise conditions was the worst of the three strategies, because the larger minimum time separations $\{\Delta t_i\}$ of the optimal strategy required that conflict-avoiding delays be longer and therefore the fuel used to absorb those delays to be greater.

Fuel usage difference results show that there is a definite fuel advantage to separating traffic by altitude when using an optimal descent strategy. For an ERM mix, the savings can be as much as 300 lb per airplane at almost 60 ACPH arrival rate, while for a JFK distribution, the advantage can be as high as about 1800 lb per airplane.

7.3 CONFLICT PERFORMANCE

Figures 17 through 22 are plots of conflict probability (susceptibility) as a function of arrival rate. Each figure compares a descent strategy's conflict performance for a particular traffic mix (JFK or ERM) between best and common cruise conditions.
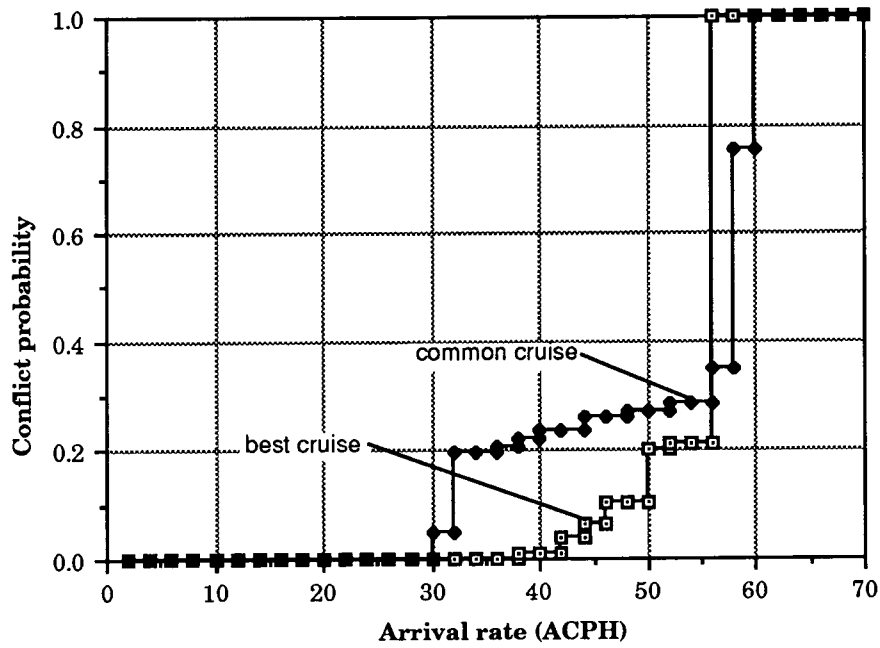
Figure 17. Conflict Probability, Optimal Strategy, JFK Mix, Cumulative Frequency Distribution
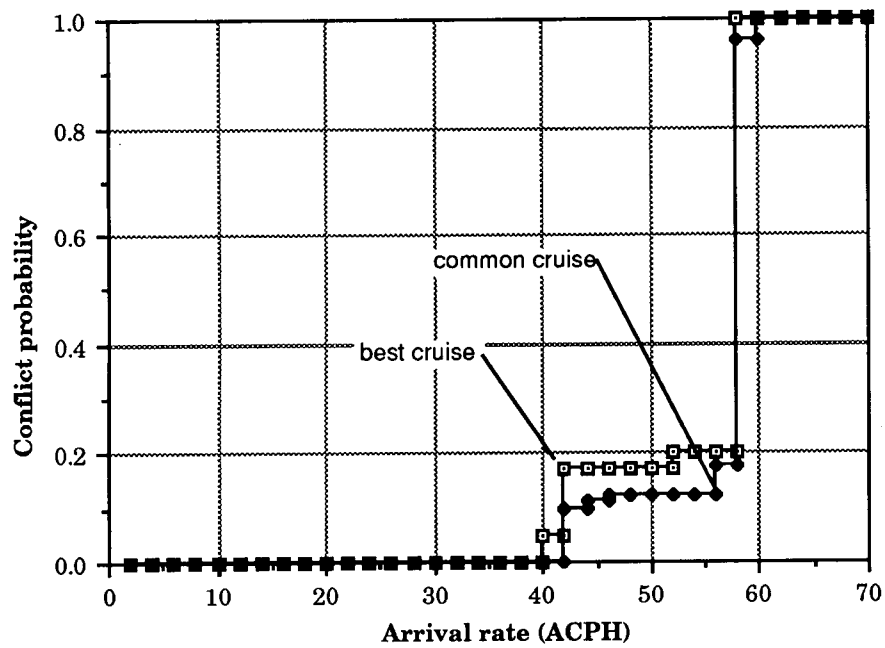

Figure 18. Conflict Probability, CFPA Strategy, JFK Mix, Cumulative Frequency Distribution

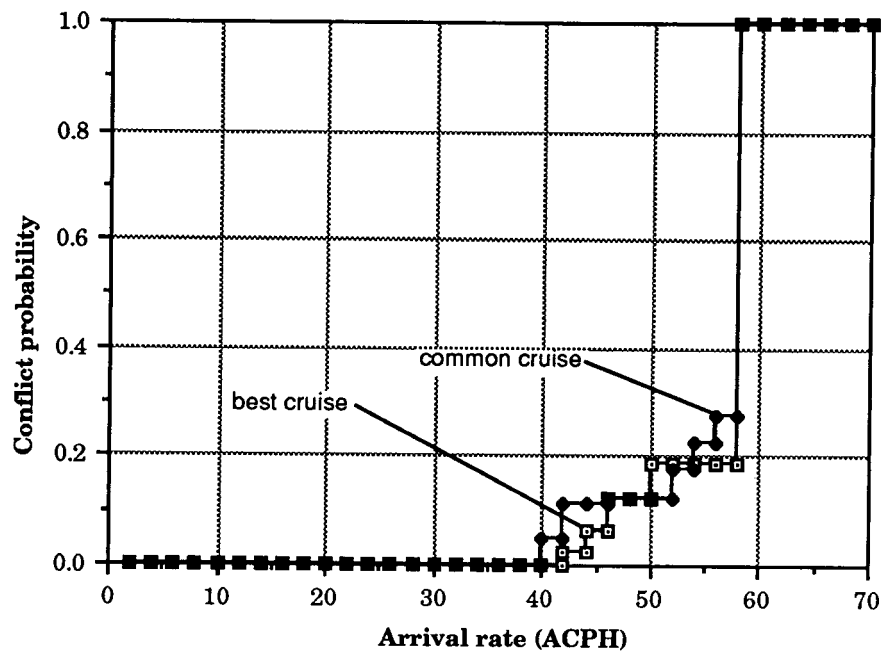**Figure 19. Conflict Probability, Clean-Idle Strategy, JFK Mix,
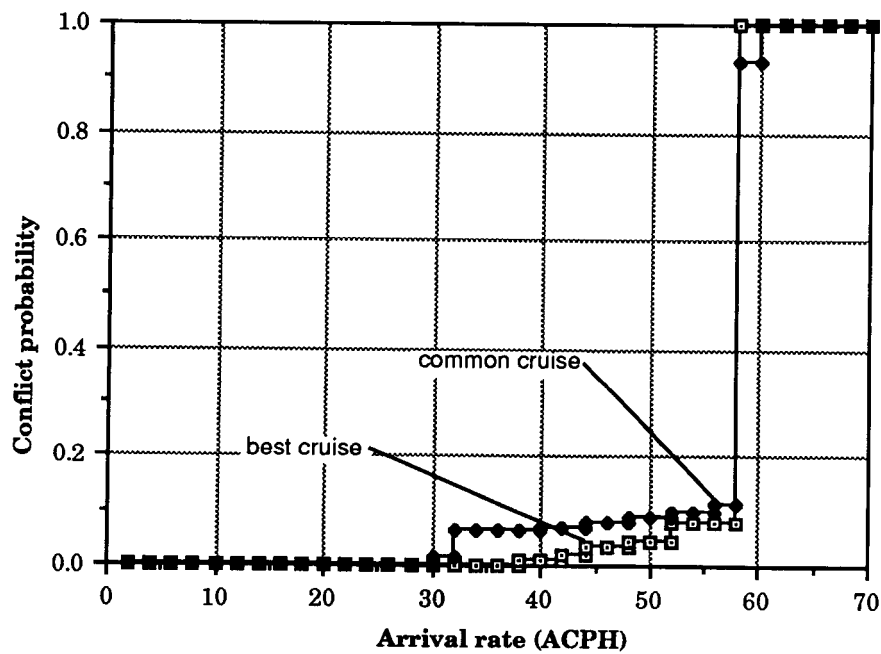Cumulative Frequency Distribution**

**Figure 20. Conflict Probability, Optimal Strategy, ERM Mix,
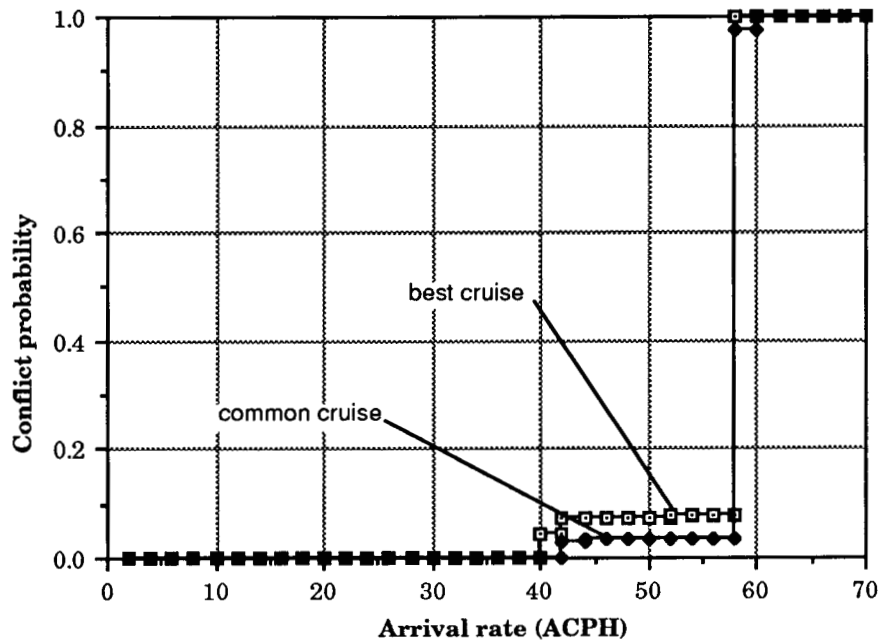Cumulative Frequency Distribution**

Figure 21. Conflict Probability, CFPA Strategy, ERM Mix, Cumulative Frequency Distribution
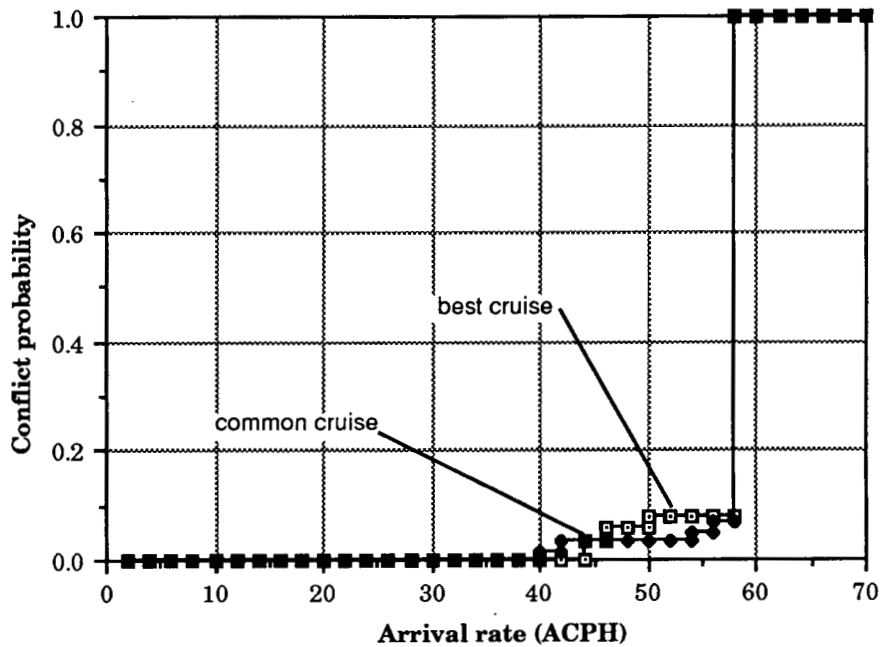

Figure 22. Conflict Probability, Clean-Idle Strategy, ERM Mix, Cumulative Frequency Distribution

Four phenomena are apparent from these figures:

1) The optimal strategy generates conflicts at lower arrival rates than either the clean-idle or CFPA strategies for both JFK and ERM mixes. While this is true to a small degree under best cruise conditions, it is most apparent under common cruise conditions, when conflicts begin at arrival rates around 30 ACPH.

2) Initial altitude separation by airplane type significantly improves the optimal strategy's conflict performance for a JFK mix. This particular result emphasizes the importance of separating airplanes with different speed characteristics by altitude to reduce conflict. In this case, the (best cruise) initial altitude separation of B737s and B747s greatly mitigates common-altitude conflicts induced by preferred speed characteristics of the respective airplanes when they employ the optimal strategy.

3) In general, the probability of conflict for a JFK mix is greater for a given arrival rate and strategy than for an ERM mix for both conditions of common and best cruise altitude.

4) The ERM mix produces conflict probabilities of around 10 percent or less up through an input arrival rate of over 57 ACPH. On the other hand, conflict probabilities of approximately 20 percent or less up through an input rate of over 57 ACPH can be expected by all strategies for a JFK mix under best cruise conditons. Only the common-cruise optimal and clean-idle over a limited range of arrival rates produced conflict probabilities in excess of 20 percent. Therefore, over most practical arrival rates and under current separation standards, conflict probabilities can be expected to roughly double when traffic distributions are more balanced between B737 and B747 types than when it consists of the B737 almost exclusively, irrespective of descent strategy.

8.0 CONCLUSIONS

The previous study (Reference 1) considered two definitions of throughput. One notion assumes that an advanced air traffic control metering program controlled arrival rate and determined landing times in such a way that minimum separation was maintained by every pair of sequential airplanes throughout their respective descents. Particular airplane pairs may initially (at cruise altitude) be separated by more than 5 nm to ensure that a conflict which might otherwise have occurred subsequently is forestalled. Hence, conflict probability is always zero. Under this assumption, it was demonstrated that the optimal strategy exhibited the lowest throughput capacity of the three strategies when traffic arrived over a common route and altitude, irrespective of traffic mix. This was primarily caused by the fact that the horizontal separation of closest approach of an optimal-strategy conflict tended to be worse than with either the clean-idle or CFPA strategy. Fewer optimal-strategy conflicts occurred at cruise altitude than with any of the other two strategies. Fuel performance of the optimal strategy was also the best among the three strategies. However, when the B737-type comprises the bulk of the total traffic (such as occurs at most metered U.S. airports), the previous study suggested that the optimal strategy be recommended because of its combination of throughput (which was only somewhat smaller than the throughputs of the clean-idle and CFPA strategies) and fuel usage performance. Nevertheless, any direct contribution by conflict performance to a relative descent strategy evaluation was not relevant.

The alternative definition of throughput discussed in the previous study was based on input traffic's entering the simulation airspace at a constant arrival rate. Therefore, at low enough arrival rates, throughput is limited by arrival rate, while at high enough arrival rates, throughput is determined strictly by minimum time separations. Even though the input rate is maintained, ATC is assumed to issue vectors *after traffic enters the simulation airspace* to prevent conflicts. This assumption implies that when such vectors are required, throughput rate can no longer match arrival rate. Consequently, the previous study indicated that at sufficiently large arrival rates, fuel usage performance of the optimal strategy under common cruise conditions became the poorest in relation to the other strategies because traffic, owing to the optimal strategy's greater conflict severity at higher arrival rates, required vectoring of greater magnitude to relieve conflict. For the very reason that average non-conflicting horizontal separations in traffic employing the CFPA strategy were the smallest among the strategies, CFPA at high arrival rates became

the best performer in terms of throughput, fuel, and conflict workload measures. Therefore, under common cruise conditions and constant arrival rate assumptions, the CFPA strategy appeared to be the strategy of choice.

These relative performance characteristics were not expected to carry over under the conditions assumed for this study. Because there was some degree of altitude separation among the different airplane types, fewer conflicts at cruise altitude (and, in fact, fewer conflicts in total) were expected to occur. Therefore, conflict pressures that primarily affected the optimal strategy in the previous study were expected to be mitigated. Conflicts after the start of descent were assumed to play a more prominent role in determining conflict susceptibility. However, conflict susceptibility and lower throughput are not necessarily correlated concepts. Conflict susceptibility represents the probability of conflict which in general is not related to average pairwise conflict-free separation (a measure of throughput).

The results of this study show that conflict susceptibility of the optimal strategy improved relative to common cruise conditions, while that of the CFPA strategy deteriorated. The optimal strategy demonstrates the most significant *change* in conflict performance where heavy and light airplanes are equally distributed (e.g., JFK mix in Figure 17).

The effect of the altitude separation appears to have been to desensitize throughput rate to descent strategy and traffic mix, that is, to allow throughput performance to be more closely *comparable* for all strategies and airplane-type distributions. This phenomenon is most pronounced for the optimal strategy whose throughput performance improved for all traffic mixes.

A Monte Carlo analysis that randomizes simulation entry point times in a representative multi-sector, multi-route feeder system will most likely produce further throughput gains, but certainly not on a scale that corresponds to the extra airspace capacity made available. This is because the throughput values are already close to saturation. The gains will probably be made in fuel usage, since fewer conflict-avoiding delays will need to be enforced on more dispersed arrival traffic; and in conflict susceptibility, which is also sensitive to traffic density.

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9.0 REFERENCES

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Report Documentation Page

1. Report No. NASA CR-4248	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Descent Strategy Comparisons for TNAV-Equipped Aircraft Under Airplane-Preferred Operating Conditions		5. Report Date August 1989
		6. Performing Organization Code
7. Author(s) K. H. Izumi		8. Performing Organization Report No.
		10. Work Unit No. 505-66-41-01
9. Performing Organization Name and Address Boeing Commercial Airplanes P.O. Box 3707 Seattle, WA 98124-2207		11. Contract or Grant No. NAS1-18027
		13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Langley Research Center Hampton, VA 23665-5225		14. Sponsoring Agency Code

15. Supplementary Notes

Langley Technical Monitor: L. Credeur
Final Report - Task Assignment 7

16. Abstract

A study was undertaken to evaluate three 4D descent strategies employed by TNAV-equipped aircraft in an advanced metering air traffic control environment. The Flow Management Evaluation Model (FMEM) was used to assess performance using three criteria when traffic enters the simulation under preferred cruise operating conditions (altitude and speed): throughput, fuel usage, and conflict probability. In comparison to an evaluation previously performed under NASA contract, the current analysis indicates that the optimal descent strategy is preferred over the clean-idle and constant descent angle (CFPA) strategies when all three criteria are considered.

17. Key Words (Suggested by Author(s)) Time Navigation, 4D RNAV, Descent Strategies, Throughput, Fuel Usage, Air Traffic Control, Conflicts	18. Distribution Statement Unclassified-Unlimited Subject Category 08

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 44	22. Price A03