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Transportation Research Record 1744

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Foreword

The papers contained in this volume were among those presented at the 80th Annual Meeting of the Transportation Research Board in January 2001. More than 1,700 papers were submitted by authors; more than 1,100 were presented at the meeting; and approximately 600 were accepted for publication in the 2001 series of the *Transportation Research Record: Journal of the Transportation Research Board.* The published papers also will be issued on CD-ROM, which will be available for purchase in late 2001. It should be noted that the preprint CD-ROM distributed at the 2001 meeting contains unedited, draft versions of presented papers; the papers published in the 2001 *Record* series include author revisions in response to review comments.

The subtitle of the *Record,* "Journal of the Transportation Research Board," reflects the nature of the publication series and the peer review conducted in accepting papers for publication. Each paper published in this volume was peer reviewed by the sponsoring committee acknowledged at the end of the text; members of the sponsoring committees for the papers in this volume are identified on page ii. Additional information about the *Transportation Research Record: Journal of the Transportation Research Board* series and the peer-review process can be found on the inside front cover. The Transportation Research Board appreciates the interest shown by authors in offering their papers and looks forward to future submissions.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials (known by abbreviation only)
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board

Paper No. 01-3024

Prospects for Increasing Average Aircraft Size at Congested Airports

Geoffrey D. Gosling and Mark M. Hansen

It has been common for airport traffic forecasts to assume a continuing increase in average aircraft size in the future so that the anticipated growth in passenger demand will not result in a proportional increase in aircraft operations. However, to understand the likely future trends in average aircraft size, as well as strategies that an airport might pursue to encourage airlines to use larger equipment, it is necessary to understand the competitive dynamics of the various markets served by the airport and the factors that determine the size of equipment that airlines will use in those markets. Recent trends in average aircraft size at a major U.S. West Coast airport and the influence of market characteristics on the size of aircraft used in different markets are examined. The changes in the past decade in selected short- and medium-haul markets are analyzed, and the results are presented of a cross-sectional model that estimates the influence of various market characteristics, including air traffic delay levels, on the average size of aircraft deployed in a wide variety of markets throughout the United States. The prospects for airport capacity constraints to influence airlines to make use of larger aircraft are discussed, and the implications for airport strategies to encourage the use of larger aircraft are examined.

The ability of major airports to accommodate future growth in air passenger traffic without experiencing severe delays at peak hours will depend in part on the future airline fleet mix. An increase in average aircraft size generally allows an airport to serve more passengers without a corresponding increase in the number of aircraft movements, although the peak period capacity of the runway system is itself affected by the mix of larger and smaller aircraft, due to differences in aircraft performance and the differing separation standards resulting from wake vortex considerations. It is common for airport traffic forecasts to assume a continuing increase in average aircraft size in the future, which will allow passenger traffic to continue to grow at a faster rate than aircraft operations. The most recent air traffic forecasts by the Federal Aviation Administration (FAA) project that the average aircraft size for domestic operations by commercial air carriers will increase from 141 seats in 1999 to 149 seats in 2011, whereas the average size of regional airline aircraft will increase from 36 seats to 44 seats in the same period (*1*).

However, changes in average aircraft size do not result from a steady increase in the size of each aircraft. Rather, they result from a change in the composition of the traffic being handled by the airport and discrete changes in aircraft size in particular markets when different aircraft types are deployed in those markets. Thus, to understand the likely future trends in average aircraft size as well as strategies that an airport might pursue to encourage favorable trends, it is necessary to understand the competitive dynamics of the various markets served by the airport and the factors that determine the type of equipment that airlines will use in those markets.

A research study for the Los Angeles World Airports has examined how airport capacity constraints at Los Angeles International Airport (LAX) are likely to influence future trends in fleet mix and the potential for alternative policy options to influence these trends. As part of this study, an analysis was undertaken of recent trends in passenger traffic and aircraft size in different types of market from LAX. This analysis was supplemented by an empirical study of the influence of airport delays on the average size of aircraft used in a large number of U.S. domestic markets.

Increasing average aircraft size is only one of several ways that airlines could respond to an increase in airport delays resulting from traffic growth. New flights could be added at less busy times of the day, service could be expanded at other airports in the region, or connecting passengers could be routed through other airports. In the case of LAX, although the increase in aircraft operations in the past 10 years appears to have resulted in increased delays, the proportion of flights delayed by 15 min or more has varied significantly from year to year. These delays increased from 0.7 percent of operations in 1990 to 2.0 percent in 1992 (*2*). They declined to 0.9 percent the following year, then increased to 2.7 percent in 1995, subsequently declining to 1.8 percent in 1997 (*3*). Although the overall trend has been upward, it is clear that changes in weather conditions from year to year can have a significant effect on delay levels.

TRENDS IN TRAFFIC COMPOSITION AT LOS ANGELES INTERNATIONAL AIRPORT

The recent traffic trends at LAX provide a good basis for studying the forces shaping airline fleet mix decisions and their implications for potential changes in airline fleet mix to accommodate growth in passenger traffic without a corresponding growth in aircraft operations. Although the situation at every major airport varies, the diversity of the markets served from LAX, together with the fact that no one airline has a dominant share of the traffic, suggests that the trends at this airport are illustrative of the factors shaping fleet composition throughout the industry.

The growth in passenger traffic at LAX since 1970 is shown in Figure 1, based on traffic statistics reported by Los Angeles World Airports. It can be clearly seen that although all market segments have experienced traffic growth, international traffic has grown faster than domestic traffic, whereas regional airline passenger traffic, although still a small proportion of total traffic, has increased significantly over the past three decades.

The corresponding growth in operations is shown in Figure 2. Although operations have not grown as fast as passenger traffic, they

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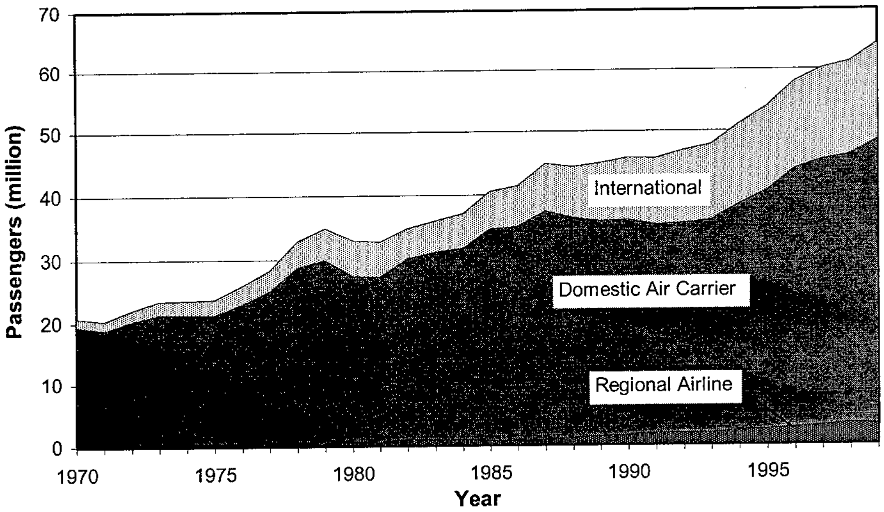

FIGURE 1 Growth in passenger traffic at Los Angeles International Airport (LAX).

have nearly doubled since 1982. Also, although the regional airlines account for a relatively small proportion of the total passenger traffic, they account for a significant share of aircraft operations. The steady growth in regional airline operations from 1986 to 1996, which accounted for about half the growth in total operations during that period, ended in 1996, and the subsequent slow decline in regional airline operations has tended to offset the growth in air carrier operations during the past 3 years.

The resulting trends in average number of passengers per operation are shown in Figure 3. After growing steadily from 1970 to the mid-1980s, the overall average number of passengers per operation declined slightly during the following decade and has been showing an upward trend since 1995. The corresponding measure for air carrier operations peaked in the early 1980s, declined over the next 4 years, and has shown a slow upward trend thereafter, although by 1999 it was still slightly below where it was 16 years before. Meanwhile, the average number of regional airline passengers per operation has shown a fairly steady growth over the entire period, although this appears to have slowed in the last year. The apparent paradox in the late 1980s and early 1990s—when the overall average number of passengers per operation declined while the corresponding measure for both air carrier and regional airline operations increased—was due to the effect of the regional airlines carrying an increasing share of the total traffic on much smaller aircraft. Whether the recent upward trend in overall average number of passengers per operation will continue thus will depend in part on the ability of both the air carriers and the regional airlines to continue increasing their average number of passengers per operation and in part on the future share of the total traffic handled by the regional airlines.

Of course, the average number of passengers per operation results from the combined effect of the average aircraft size and average load factor (proportion of seats occupied). Although airline fleet mix decisions directly influence average aircraft size, consideration also must be given to the effect of changes in load factor. The relative effects of these two factors for domestic air carrier operations over the 11-year period from 1988 to 1999 are shown in Figure 4. It can

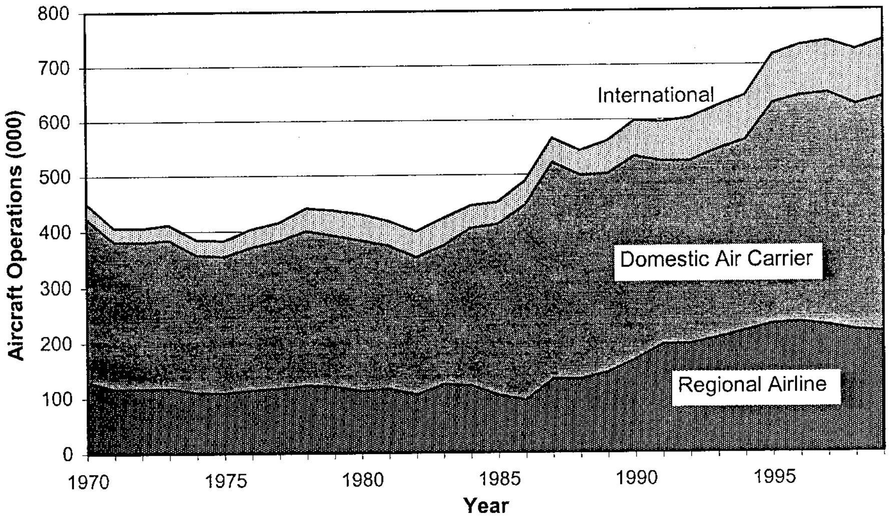

FIGURE 2 Growth in aircraft operations at LAX.

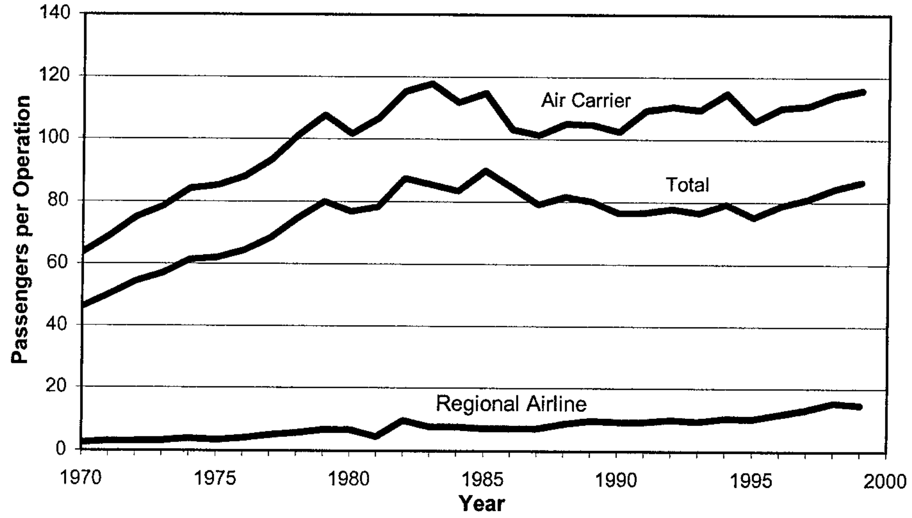

FIGURE 3 Trend in average number of passengers per operation at LAX.

be seen that the modest growth in passengers per operation is due entirely to increases in load factor rather than aircraft size, which has in fact declined over the period. There are obvious limits to how long an increase in load factor can continue.

Since 1995, the steady growth in average number of passengers per operation for the regional airlines shown in Figure 3 has more than offset the growth in regional airline passenger traffic, resulting in the slow decline in regional airline operations since 1996 shown in Figure 2.

RECENT TRENDS IN SHORT- AND MEDIUM-HAUL MARKETS

Short- and medium-haul markets in the western states, including the California corridor between Southern California and the San Francisco Bay Area, accounted for 10 of the 20 densest domestic markets from LAX in 1999, with Las Vegas, Nevada, and San Francisco the largest and second largest markets respectively. The majority of these markets involve both frequent service and use of relatively small aircraft. Therefore, examination of the recent trends in these markets provides a useful perspective on the factors that appear to be influencing the size of equipment used in such markets and the prospects for increasing average aircraft size.

Changes during the past 11 years in both traffic and average aircraft size in these eight markets are shown in Table 1. Passenger traffic grew significantly in most markets from 1988 to 1999, with the exception of San Francisco, where it declined by 13 percent. However, traffic growth to the two other Bay Area airports (Oakland and San Jose) more than offset the decline in traffic to San Francisco, with traffic to Oakland growing more than threefold. The changes in average aircraft size in these markets during the period show that this has increased in all but two markets (San Francisco and Seattle), although the changes appear to be unrelated to the amount by which the traffic has increased in each market. Overall in the 10 markets, the average aircraft size increased from 136 seats to 139 seats during the period, an increase

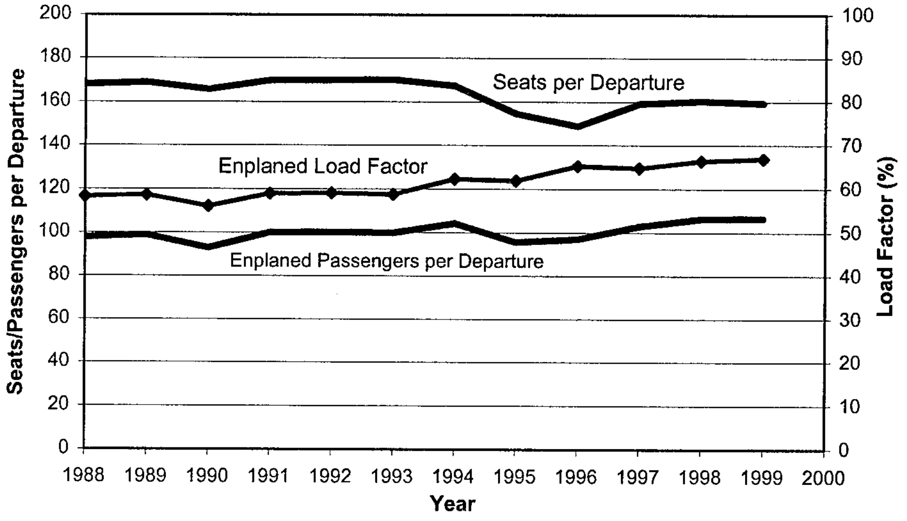

FIGURE 4 Trend in domestic air carrier market characteristics at LAX.

TABLE 1 Changes in Largest Short- and Medium-Haul Markets from LAX

	Segment Traffic (passengers)		Average Aircraft Size (seats)	
Destination	1988	1999	1988	1999
Las Vegas	959,694	1,719,481	131	136
San Francisco	1,715,731	1,325,173	142	130
Phoenix	1,156,276	1,268,910	128	131
Oakland	282,335	957,725	118	132
Denver	782,667	874,100	175	187
San Jose	625,101	839,185	117	130
Seattle	556,055	774,091	152	144
Salt Lake City	252,445	586,963	166	184
Sacramento	302,760	536,193	117	132
Portland	230,564	480,154	135	136

SOURCE: U.S. Department of Transportation, Form 41, Schedule T-100 (Data Base Products Onboard dataset)

of about 2 percent at a time when the total traffic in these markets grew by 36 percent.

Closer examination of the traffic and aircraft size data for individual markets showed that the changes were by no means uniform over the period, and aggregate data at the market level conceal significant changes in market share and concentration. Several markets became significantly more concentrated by 1999, with United Airlines carrying almost 80 percent of the traffic in the LAX–San Francisco market, Southwest Airlines carrying more than 75 percent of the traffic in the LAX-Oakland market, and Alaska Airlines carrying 70 percent of the traffic in the LAX-Seattle market. In other markets, the changes were more complex, with Southwest and United Airlines generally increasing their market share at the expense of the incumbent carriers in 1988. However, in spite of this increase in market concentration, there was very little, if any, increase in average aircraft size by the dominant carriers over the period. Almost all the markets showed an increase in load factor over the period, which resulted in an increase in passengers per departure, even if the average aircraft size did not increase.

The effect of changes in airline market share on the average aircraft size in a market are illustrated by the changes between 1988 and 1999 in market share and average aircraft size for the principal airlines serving the LAX-Seattle market (see Figure 5), one of the few markets to experience a reduction in average aircraft size.

In 1988, the LAX-Seattle market was fairly evenly divided between Alaska Airlines, Delta Airlines, Pacific Southwest Airlines (PSA), and United Airlines. During 1988 PSA was absorbed by USAir. During the following 11 years, Alaska increased its market share from about 25 percent to about 70 percent, whereas United maintained its market share at around 30 percent. USAir experienced a rapid loss of market share and withdrew from the market in 1991, whereas Delta experienced a steady erosion of market share and by 1998 had essentially withdrawn from the market. The average aircraft size operated by Alaska increased during the period from 134 seats in 1989 to 140 seats by 1995, where it has remained since then. The average aircraft size operated by United declined from 143 seats in 1988 to 118 seats in 1994, then increased steadily to 156 seats in 1999. However, Delta had consistently operated the largest equipment in the

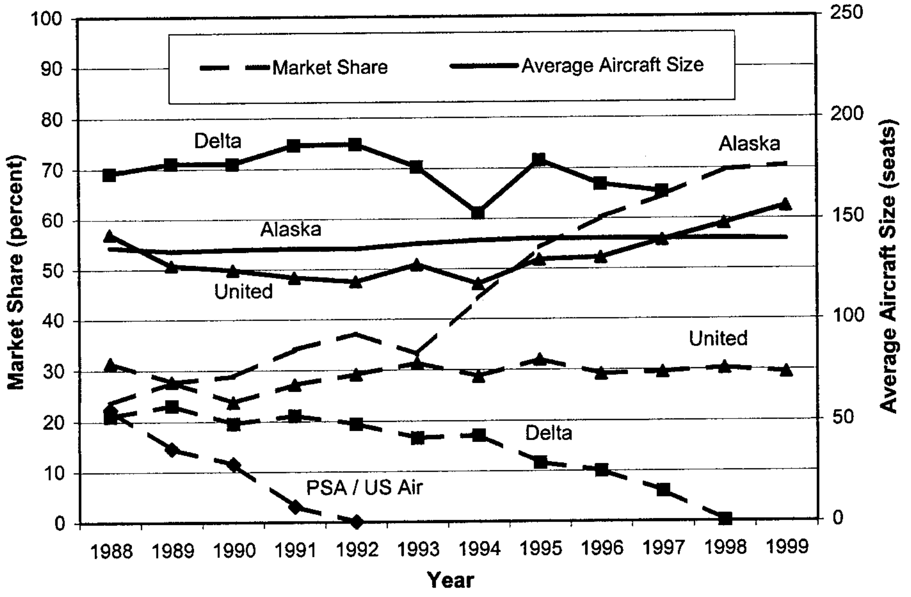

FIGURE 5 Market share and aircraft size trends in LAX-Seattle market.

market, with an average aircraft size that varied between 153 seats and 187 seats. Thus the reduction in average aircraft size in the market between 1988 and 1999 is due entirely to discontinuation of service by Delta, and in fact the average aircraft size operated by both Alaska and United increased slightly over the period. Even so, in spite of a fourfold increase in traffic carried in the market, Alaska increased its average aircraft size by only about 4 percent.

The changes in average aircraft size in the other nine markets were influenced by similar changes in airline market share interacting with changes in equipment operated in the market by each airline, and a detailed analysis of all 10 markets is provided by Hansen, Gosling, and Margulici (*4*).

FACTORS INFLUENCING AIRCRAFT FLEET MIX

To better understand the factors that influence fleet mix, regression analysis was used to study the relationship between the average size of aircraft flown on U.S. domestic service segments and segment characteristics such as traffic level, segment length, and congestion at the endpoint airports. The basic specification of the regression models is the following:

$$SPF = f(pax, length, concentration, delay) \qquad (1)$$

where

SPF = the average number of seats per flight on the segment,
pax = the average segment traffic per day,
$length$ = segment length (statute miles),
$concentration$ = the segment concentration (calculated as the sum of the squared airline traffic shares on the segment—known as the Herfindahl-Hirschman index), and
$delay$ = the average arrival delay at the endpoint airports (minutes).

Various other segment characteristics, such as the number of passengers with a trip origin and destination at the segment endpoints, also were investigated. Attempts to include them in the model formulation generally resulted in statistically insignificant parameter estimates, however, and they were not used in the model calibrations presented in this paper.

The models were estimated on a data set consisting of domestic flight segments originating from the 18 major U.S. airports listed in Table 2. The set includes all the major airports on the east and west coasts. Interior airports were not included because the larger airports are major hubs, which are dominated by connecting traffic. Such airports are nonetheless represented in the data set because they are the endpoints for many of the segments originating from the 18 study airports.

Data for the number of flights flown, the number of seats, and the number of passengers carried on scheduled service by certificated carriers for each nonstop segment from the study airports in 1998 were obtained from data reported to the U.S. Department of Transportation (DOT) on Schedule T100, using the Onboard data set from Data Base Products, Inc. Traffic carried by commuter airlines on each of these segments was also estimated by combining data for regional airlines in the T100 data set with online, origin-destination data for commuter carriers reporting on Schedule 298C. Segments for which the proportion of traffic carried by commuter airlines exceeded 20 percent were discarded, as were those that did not average at least one flight per day by certificated carriers. Altogether, this resulted in 526 segments involving the 18 study airports.

The stage length for each segment was obtained from the Onboard data set. Delay data were obtained from a study by Citrenbaum and Juliano (*5*), who used the U.S. DOT Airline Service Quality Performance (ASQP) database to calculate average arrival delay (the difference between actual arrival time and scheduled arrival time) and flight delay (actual flight time less scheduled flight time) for major U.S. airports.

The relationship between the average number of seats per flight and the segment density (passengers per day) is shown in Figure 6 for each

TABLE 2 Characteristics of Airports in the Model Calibration

Airport	Code	Total Domestic Segment Passengers, 1998 (millions)	Commuter Airline Share (percent)	Average Seats per Certificated Airline Departure	Average Arrival Delay[1] (minutes)
Boston	BOS	10.1	9.2	145	15.3
Baltimore/Washington	BWI	6.8	7.2	137	11.7
Washington National	DCA	7.3	6.4	133	11.1
Newark	EWR	12.5	9.3	139	19.8
Fort Lauderdale	FLL	5.3	2.0	147	15.0
Washington Dulles	IAD	4.5	16.6	147	12.5
New York Kennedy	JFK	6.6	13.4	187	18.6
Los Angeles International	LAX	21.6	6.9	160	15.2
New York LaGuardia	LGA	10.0	5.4	142	12.8
Orlando	MCO	11.7	4.5	148	14.1
Miami	MIA	8.2	11.0	169	14.7
Oakland	OAK	4.8	0.0	134	9.7
Portland	PDX	6.2	12.4	142	14.9
Philadelphia	PHL	9.6	10.4	128	12.5
San Diego	SAN	7.0	6.2	143	12.7
Seattle-Tacoma	SEA	11.9	7.7	144	14.5
San Francisco International	SFO	15.5	3.7	159	19.1
Tampa	TPA	6.4	8.2	145	14.9

[1] Based on ASQP data for 1997.

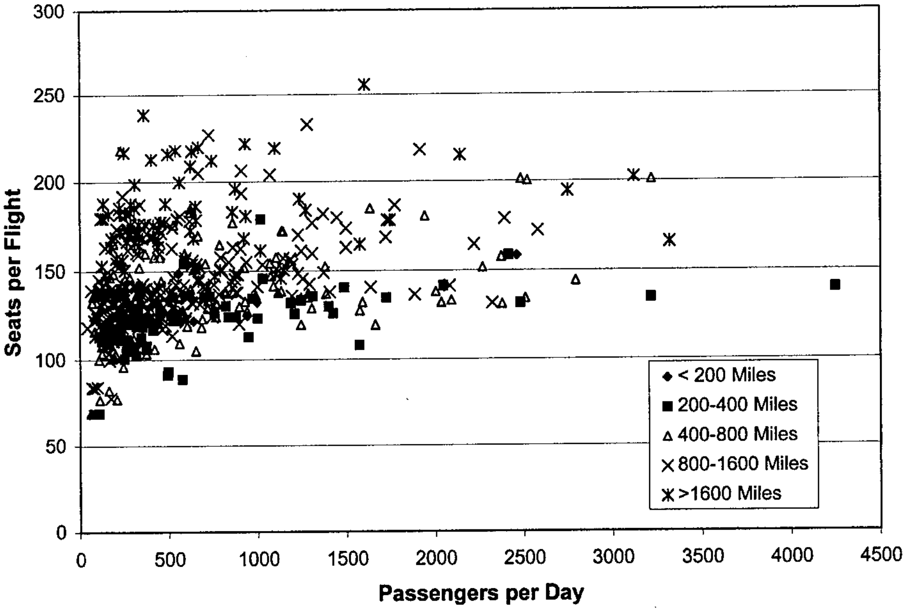

FIGURE 6 Variation of average aircraft size with market density—certificated segments.

of the 526 flight segments with certificated service originating at the 18 study airports. The points are coded by segment length, as shown in the legend included with the figure. The data points have a large amount of scatter but also reveal clear patterns. When segment density is low—less than about 300 passengers per day—average aircraft size increases rapidly with traffic. In this regime, traffic growth is accommodated mainly through increasing aircraft size. This is presumably because the cost savings from doing so outweigh the benefits from increasing service frequency. It may also reflect the effect of the "indivisibility" problem on low-density segments, where adding a daily flight entails a large fractional increase in capacity, whereas upsizing an existing flight permits a smaller increment in capacity.

Once segment density increases beyond about 300 passengers per day, its effect on average aircraft size diminishes. For segments less than 643.7 km (400 mi) in length, average aircraft size levels off at about 130 seats per flight, even for segments with several thousand passengers per day, which as a result must have daily frequencies of several dozen flights. On longer segments, aircraft size levels off more gradually, at higher values and with greater variability. For example, for segments longer than 2574.9 km (1,600 mi) the average size reaches about 220 seats, but individual segments have values as high as 250 and as low as 170. As will be shown below, much of this variation can be explained by the other factors included in the analysis.

The segment data were used to estimate regression models that explain the variation in average seats per flight. The models were of the following form:

$$\ln(SPF_{ij}) = \alpha_0 + \alpha_i + \sum_k \beta^k X_{ij}^k + \epsilon_{ij} \qquad (2)$$

where

SPF_{ij} = the average number of seats per flight (total seats/total flights) for the segment between origin i and destination j;
α_0 = a constant intercept term, to be estimated in the regression;
α_i = an origin-specific constant term, to be estimated, with the constant for LAX set to zero, making it the "reference" airport;
β^k = the regression coefficient on the kth independent variable, to be estimated;
X_{ij}^k = the value of the kth independent variable for segment with origin i and destination j; and
ϵ_{ij} = a stochastic error term for the segment with origin i and destination j.

The independent variables used in the model are defined in Table 3. The last three variables in the table attempt to reflect interactions between stage length and the other independent variables, based on the expectation that the sensitivity of average aircraft size to the various independent variables may depend on length of the flight segment.

In light of the results from the graphical analysis discussed above, the data were divided into two subsets based on whether the segment density exceeded 300 per day. The segments meeting this criterion were termed "high-density" segments; the others were "low-density" ones. Separate models were estimated for these two subsets. In addition, it proved useful to subdivide the high-density segments into short-haul [length less than 804.7 km (500 mi)] and medium/long-haul segments [length of 804.7 km (500 mi) or more, and termed "long-haul" for brevity]. The stage length interaction variables were considered only for the high-density, long-haul segments, because only this data set contained sufficient observations and distance variation to make interaction effects estimable.

Estimating the models began with a model containing all the potential independent variables that had been considered. Then variables that proved statistically insignificant were eliminated until arriving at the models shown in Table 4.

High-Density, Short-Haul Segments

It was found that aircraft size on these segments depends largely on density and concentration. In the final model, shown in Table 4, both of these variables are highly significant statistically, and their

TABLE 3 Definition of Model Independent Variables

Variable	Definition
PPD	Natural log of segment traffic density, in passengers per day
SL	Natural log of the segment length, in statute miles
HHI	Natural log of the segment Herfindahl-Hirschman Index for airline traffic shares
ARD	Natural log of the arrival delay averaged over the segment origin and destination airports, in minutes
PPD*SL	Product of variables PPD and SL
HHI*SL	Product of variables HHI and SL
ARD*SL	Product of variables ARD and SL

coefficients have similar magnitudes of about 0.13. Because the model is log-linear, this implies that a 10 percent increase in segment density or concentration will result in a 1.3 percent increase in aircraft size. The adjusted R^2 of 0.47 implies that this model explains about half of the observed intersegment variation in aircraft size, whereas the standard error of 0.10 implies that model predictions are accurate to about 10 percent.

The airport constants in the preferred model are mostly insignificant, with the exception of the constant for Seattle. Most of the estimates are also negative, implying that, relative to the reference airport, LAX, these airports are served by smaller aircraft in their high-density, short-haul markets, all else equal. Although several airports, including Orlando and Tampa, have positive estimates, in no case are these statistically significant. From this, it was concluded that for high-density, short-haul segments served by certificated carriers, average aircraft sizes at the other airports in the study are not significantly different from the pattern observed in segments from LAX.

TABLE 4 Model Calibration Results

	Estimated Parameter Values		
Variable	High Density, Short-Haul Segments	High Density, Long-Haul Segments	Low Density Segments
PPD	***0.124***[1]	***0.580***	***0.204***
SL	N/A	***-1.019***	***0.159***
HHI	***0.130***	N/A	***0.123***
ARD	N/A	***-3.292***	N/A
PPD*SL	N/A	**-0.066**[2]	N/A
HHI*SL	N/A	***0.027***	N/A
ARD*SL	N/A	***0.532***	N/A
Constant	***2.910***	***8.615***	**1.493**
BOS Constant	-0.053	**-0.080**	0.119
BWI Constant	0.020	-0.042	**0.142**
DCA Constant	0.007	***-0.103***	0.049
EWR Constant	-0.053	***-0.189***	0.026
FLL Constant	-0.124	-0.015	0.016
IAD Constant	-0.096	0.063	**0.110**
JFK Constant	0.000	0.068	***0.387***
LGA Constant	-0.027	-0.059	0.053
MCO Constant	0.122	-0.020	***0.214***
MIA Constant	0.000	0.045	***0.172***
OAK Constant	-0.045	-0.022	**0.202**
PDX Constant	-0.011	-0.008	0.084
PHL Constant	-0.069	***-0.126***	-0.018
SAN Constant	-0.028	-0.032	0.120
SEA Constant	***-0.262***	-0.039	0.015
SFO Constant	-0.048	***-0.104***	**0.136**
TPA Constant	0.120	-0.050	**0.135**
Adjusted R^2	0.46	0.56	0.47
Standard Error	0.10	0.11	0.16

[1] Coefficients in ***bold italics*** are significant at the 1% level, two-tailed test

[2] Coefficients in **bold** are significant at the 5% level, two-tailed test

High-Density, Long-Haul Segments

Estimation results for long-haul segments are also shown in Table 4. The final model has an adjusted R^2 of 0.56 and a standard error of 0.11 (indicating a predictive accuracy of about 11 percent). The long-haul model is considerably more complex than the short-haul model. The significant factors are density, concentration, stage length, and delay. Market density and delay appear both individually and in interaction with stage length, whereas for concentration only the stage length interaction is included. Density is positively related to aircraft size, but the effect declines as stage length increases. Delay, however, becomes more important at longer stage lengths. Its individual coefficient is negative, but the overall effect of delay [calculated as $-3.292 + 0.532 * \ln(SL)$] is approximately 0 at stage lengths of 804.7 km (500 mi), increasing to about 0.9 for 4023.4-km (2,500-mi) segments. For similar reasons, increased stage length leads to larger aircraft despite the negative coefficient on the individual stage length term. Aircraft size is more sensitive to stage length when segments have low densities, high delays, and high concentrations.

Several of the airport constants are negative and statistically significant, including those for Boston, Washington National, Newark, Philadelphia, and San Francisco. All else equal, these airports have aircraft sizes 10 to 20 percent smaller than LAX. Three airports—Washington Dulles, New York Kennedy, and Miami—have sizes slightly, but not statistically significantly, higher. Thus, for long-haul as well as short-haul segments, it was concluded that the majority of other airports considered in this study are similar to LAX in terms of the average size of aircraft used on segments of given characteristics.

Low-Density Segments

Table 4 summarizes estimation results for segments with fewer than 300 passengers per day served by certificated carriers. The model covers all stage lengths, because there are insufficient data to estimate separate short-haul and long-haul models. In the final model, average aircraft size increases with traffic density, segment length, and segment concentration, with all three relationships significant at the 1 percent level. An increase of 10 percent in each of these variables is associated with aircraft size increases of 2.0, 1.6, and 1.2 percent, respectively. The model explains about half of the variation in aircraft size observed in the sample.

Most of the airport constants are positive, in many cases significantly so. This means that, controlling for other factors, low-density segments from these airports tend to be served by larger aircraft than at LAX. The magnitude of this difference exceeds 10 percent in several cases, and in the case of New York Kennedy it exceeds 60 percent.

INFLUENCE OF CAPACITY CONSTRAINTS ON FLEET MIX

Even if no explicit actions are taken by airport authorities to encourage the use of larger aircraft, growing delays may cause airlines to begin to use larger aircraft. However, their ability to do this is constrained by two factors. The first is their overall fleet and how aircraft are routed across their network. Typically, aircraft do not travel back and forth in a market, but move through the network over the course of the day. Although there may be enough traffic in a given market to justify a larger aircraft, that may not be true for subsequent flight segments of that aircraft's itinerary. The second constraint is the competitive situation in each market. The more airlines serving a market, the smaller the passenger traffic handled by each airline, and thus the lower the average passenger load on each aircraft for a given frequency of service.

This has two implications. The first is that there are both short-run and longer-run decisions that affect the ability of an airline to use larger aircraft. In the short run, the airline is constrained by the aircraft that it has in its fleet, although in the longer run, it could add new aircraft to the fleet. The second implication is that understanding how airlines are likely to respond to capacity constraints or airport policies to encourage the use of larger aircraft requires a careful analysis of the economics of serving the market, including competitive effects. Flight frequency affects market share, and no airline will want to put itself at a competitive disadvantage so that other airlines can experience the benefits of reduced congestion.

The foregoing analysis has suggested that airlines tend to use larger equipment in long-haul, high-density markets with high levels of delay, with the effect of delay increasing with stage length. No effect of delay was observed in short-haul, high-density markets, where flight frequency is likely to be more important than on longer segments, or in low-density markets. The analysis has also shown that larger aircraft tend to be used in denser markets and those with greater market concentration. As might be expected, average aircraft size tends to be larger in long-haul, high-density markets than in short-haul, high-density or low-density markets. Even so, in the long-haul, high-density market model, a 10 percent increase in traffic results in only about a 2 percent increase in average aircraft size for segments of 804.7 km (500 mi), reducing to less than 1 percent for segments of 4023.4 km (2,500 mi). The effect of market density in the short-haul, high-density and low-density models is independent of segment length, and a 10 percent increase in traffic gives about a 1 percent increase in average aircraft size for short-haul, high-density segments and about a 2 percent increase for low-density segments.

The effect of a change in market concentration in a two-carrier market from the largest carrier having 60 percent of the market to having 70 percent of the market is to increase the Herfindahl-Hirschman index by about 12 percent. This will increase the average aircraft size by about 1.5 percent in both the short-haul, high-density and low-density models. The effect varies with segment length in the long-haul, high-density model, from a 2 percent increase in average aircraft size for an 804.7-km (500-mi) segment to about a 2.5 percent increase for a 4023.4-km (2,500-mi) segment.

CONCLUSIONS

It is clear from an analysis of traffic patterns at LAX over the past 10 years that in spite of the significant growth in passenger traffic, there has been very little, if any, increase in average aircraft size by the large domestic and international airlines. There has been a significant increase in average aircraft size by the regional airlines, resulting largely from the replacement of aircraft with 19 or fewer seats by aircraft in the 30-to-35 seat range. However, the regional airlines currently serving LAX so far have not deployed aircraft larger than 35 seats in any of the markets, and it is unclear whether further growth in the regional airline markets will be served through an increase in frequency or the introduction of larger aircraft.

Although the growth in aircraft operations during the past 10 years appears to have leveled out in the past 3 years, this is largely the result of shifts in traffic composition, and further growth in passenger traffic is likely to result in the resumption of growth in aircraft operations. The analysis presented in this paper suggests that airline response to the resulting increase in delays that will inevitably occur appears likely to result in only modest increases in average aircraft size, if left to market forces. In any event, airlines cannot deploy aircraft that they do not have in their fleets, and therefore any significant increase in average aircraft size is likely to be a slow process.

On balance, the prospects for a large enough increase in average aircraft size over the next decade at airports such as LAX to accommodate the expected growth in traffic are not very encouraging. Delay costs alone do not appear sufficient to offset the competitive advantages of greater flight frequencies, particularly in short-haul and low-density markets. Therefore airports and the federal government may need to consider potential regulatory or policy actions to encourage the use of larger aircraft if significant future increases in delay levels are to be avoided.

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Lessons from Airport Privatization, Commercialization, and Regulation in the United Kingdom

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The possible lessons of airport privatization, commercialization, and regulation in the United Kingdom (U.K.) are discussed. This is both timely and topical because of the huge financial pressures on governments to meet the infrastructure investments required to accommodate the forecasts of growth in air traffic and modernization such as new, larger aircraft. In response to these trends, the U.S. government and governments around the world have looked at the U.K. as a model of privatization. It was the first nation to privatize its airports, and a variety of ownership structures have been adopted. The history of privatization, commercialization, and regulation in the U.K. is traced, and important lessons are highlighted. Regulation may be the only policy lever available to shape a privatized and commercialized airport system and its role within a wider integrated transport strategy. The authors contend that a commercialized model of ownership similar to that at many U.K. municipal airports could be adopted in the United States, potentially relieving the financial pressure on the federal government to fund development. Countries need to have a strategic airports policy to guide development toward national, economic, and environmental goals.

Airports traditionally have been regarded as facilities to be publicly owned, operated, and subsidized. Since the mid-1980s, there has been a significant shift in many countries toward private-sector funding of airport development and operating airports on a commercial basis. The experiences of the last 14 years provide an important case study for policy makers worldwide to evaluate as they seek to assess the extent to which, if at all, they should privatize and/or commercialize their airports.

Today more than 50 countries already have introduced some kind of private-sector involvement into the ownership, financing, and/or management of their airports. The longest-standing example of airport privatization began in the United Kingdom (U.K.) under the Thatcher government with the privatization of the British Airports Authority (now BAA plc) in 1987. In addition to the privatization of BAA, 16 local authority–owned airports were commercialized. Much has already been written about the BAA model of privatization and its controversies (*1–3*). Indeed the General Accounting Office (GAO) (*4*) has cited the British case as an example that has been long-standing enough to provide tangible results in a report that seeks to identify funding sources for future airport development in the United States. The report (*4*) concentrated on the U.K. example of the major BAA airports but did not consider the alternative U.K. models offered by the diverse range of ownership structures that have developed across the different municipally owned airports. The less glamorous but valuable experience of the commercialized local authority airports has largely been ignored. These may well offer a more suitable alternative for many U.S. airports.

The aim of this paper is to explore the lessons that policy makers and regulators can draw on from the experiences of privatization, commercialization, and regulation of the local authority–owned airports in the U.K. The pressures for privatization, the experience of the U.K., and the range of airport performance under different forms of ownership are explored. The lessons from the U.K. experience of former local authority airports are discussed in relation to the United States, and conclusions are drawn.

PRESSURES ON GOVERNMENTS TO CHANGE THE OWNERSHIP STRUCTURE AND FUNDING OF AIRPORTS

It is estimated that $350 billion will be required worldwide to fund future development to accommodate growth up to 2010 (*5*). Such pressures have led governments around the world to consider privatization and commercialization to relieve themselves of the financial burden of airport ownership (*6–8*). Governments have been aware that privatization of the BAA lifted the financial burden of development from the U.K. government and provided increased resources for services such as health, education, and welfare.

The major commercial airports in the United States are publicly owned. The national airport system consists of 3,304 airports, all owned by the local, state, or municipal authorities. Expansion is funded through a mixture of tax-exempt bonds issued by the airport authorities or the owning state, passenger facilities charges, and central government grants distributed through the FAA Airport Improvement Program (*9*). Nearly 80 percent of centrally allocated funding is spent on the 71 largest airports (*8*). A variety of charging mechanisms and relationships exists between the airport and the airlines, but the level of profit an airport can make is strictly regulated.

The need for funds to expand airport infrastructure is intense. Traffic in the United States is forecast to increase 60 percent between 1999 and 2009, from 500 million passengers per annum to 800 million passengers per annum (*10*). New, large aircraft such as the Boeing 747-X and the A3XX, described elsewhere (*11*), will require new investment and design of facilities to cope with the processing of passenger loads of up to 1,000 people and new airside design specifications that will affect gate, taxiway, and apron configurations.

Between 1997 and 2001, it was estimated that $10 billion per year was required for capital development at the nation's airports (*8*). In

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1999 alone, $2.41 billion was spent through the Airport Improvement Program, and $3.2 billion has been approved for fiscal year 2001 (*9*). The GAO has estimated a need for $1.38 billion to be spent on airport pavements alone over the next 10 years (*12*). Funding shortfalls can be identified relative to the costs of planned developments specified in the National Plan of Integrated Airport Systems (NPIAS) (*13*). Shortfalls are estimated to hit medium to small airports hardest, leaving them up to 50 percent short of the funds they require to cover development costs. Large airports are forecast to suffer a 20 percent deficit in development funding (*14*). Other than by some sort of private finance, how can this shortfall be met? If the federal grant allocation were raised, then this would benefit the medium to small airports, whereas the large airports would be the main beneficiaries if the passenger facility charge were raised. The next section looks at the experiences of various private-sector involvements in the U.K. and what they can offer by way of examples for the United States.

BACKGROUND TO PRIVATIZATION AND COMMERCIALIZATION: 1986 AIRPORTS ACT

There are many different interpretations of what exactly is meant by the terms privatization and commercialization. Privatization can be defined as the transfer by governments to private investors of the assets of publicly owned enterprises, so that the new entity gains a legal status that enables it to act as a private company (*15, 16*). Commercialization can be defined as the introduction of commercial objectives to a publicly owned enterprise. These objectives can include increasing the utilization of assets, maximization of revenue, minimization of costs, and a more customer-focused approach to business (*17*, p. 4). Barrett has carried out various short case studies on the commercialization of European Airports (*18*). This section of this paper, however, concentrates on the U.K. experience and in particular non-BAA airports. The gap in the literature in this area is addressed here to offer exemplars for adoption elsewhere.

With passenger demand forecast to double between 1986 and 2005 (*19*) and infrastructure investment inevitable, the Airports Act was introduced, as part of the Conservative Government's policy to reduce the financial burden to the state of government-owned undertakings. Between 1979 and 1991, more than 50 percent of the public sector in the U.K. was transferred to the private sector, and the public-sector deficit disappeared (*15*, p. 463). The government's main policy objectives were (*19*, p. 5)

- To encourage enterprise and efficiency in the operation of major airports by providing for the introduction of private capital;
- In general to minimize subsidizing of air transport facilities by the ratepayer or taxpayer (airports, whoever their owners, should normally operate as commercial undertakings); and
- To ensure that all U.K. airports maintain the highest standards of safety.

U.K. airports were owned by either central or local government until the 1986 Airports Act decreed that by April 1, 1987, the airports of the British Airports Authority should be transferred from government ownership into a private company, publicly quoted on the stock exchange (*20*). Seven airports—Heathrow, Gatwick, Stansted, Prestwick, Aberdeen, Edinburgh, and Glasgow—were set up as limited companies that were subsidiaries of the BAA plc. These airports were now required to self-finance future development and were made responsible to shareholders. To protect national interests and to deter hostile takeover bids, the U.K. government retained a "golden share," which gives it the right to intervene, a power that to date has not been exercised.

The 16 airports that had more than £1 million (£1 = U.S. $1.42, June 2001) turnover in 2 of the previous 3 years were transformed from municipal undertakings into Companies Act companies by part 2 of the Airports Act (*20*, p. 10). Each municipal authority was given the shares of its airport company and made responsible for making a profit. Municipal owners could no longer subsidize their airports. By 1993–94, infrastructure expansion could be funded only from internal sources because the government reduced the amount of money available for airports to borrow to a negligible level (*21*).

The act gave airport management the freedom to set airport charges and staff wages, activities that previously had been determined by national committees. Municipal airport owners were now free to sell all or some of their shares to the private sector.

To protect the interests of airport users against possible pricing or other monopoly abuses, the government appointed the Civil Aviation Authority (CAA) to the role of economic regulator of airport charges and accounts. Airports were now forced to disclose revenue and expenditure attributable to airport charges, other operational activities, and nonoperational activities (*22*). The CAA continued its role as the regulator of airport safety and operational standards through the issue of a license to permit each airport to operate. Control of development was left to the planning system.

The Airports Act commercialized 16 small and medium-sized municipally owned airports responsible for about 30 percent of passengers at U.K. airports, effective April 1, 1987 (see Table 1). To assess the appropriateness of this approach, it is important to address the following questions: What was the impact of the act on airport performance, and what lessons can policy makers and governments assessing commercialization and privatization options learn from the experiences of these airports?

The full effects of the 1986 Airports Act are difficult to isolate because a range of factors has contributed to the changes that have taken place. A postal survey of senior management staff at the 16 municipal airports affected by the Airports Act part 2 was undertaken. All replied. This survey was supplemented by site visits and face-to-face interviews with airport staff, a survey of airport traffic growth, financial statistics, and a survey of business activities.

PRIVATIZATION, COMMERCIALIZATION, AND REGULATION: EXAMPLE OF U.K. MUNICIPAL AIRPORTS

By 2000, there were also government-owned essential service airports in Scotland, the privately owned BAA airports, and other privately owned airports. Five categories of ownership prevailed among the commercialized municipal airports in the U.K. (Figure 1).

- Airport sold by the local authority and now fully owned by a private company;
- Commercialized limited company with the shares partly owned by the local authority and partly owned by a private company;
- Commercialized limited company with local authority ownership of all the shares;
- Airport managed, operated, and developed by a private company as a concession controlled by commercialized limited company with local authority ownership of all the shares; and
- Partly owned by local authority and another commercialized local authority–owned airport company (source: authors' survey).

TABLE 1 U.K. Regional Airport Statistics, 1986–87 to 1998–99 (*22, 24*)

Airport	Terminal Passengers (millions)		% Change	REV/EX RATIO		% Revenue from Commercial Sources	
	1986/7	1998/9	1986/7-1998/9	1986/7	1998/9	1986/7	1998/9
Manchester	8.609	17.405	+102	1.80	1.34	31	50
Birmingham	2.091	6.716	+221	1.53	1.43	26	42
Luton	1.962	4.385	+124	1.34	1.22	36	61
Newcastle	1.335	2.988	+124	1.48	1.51	19	34
East Midlands	1.122	2.140	+91	1.48	1.66	25	38
Bristol	0.469	1.824	+289	1.28	1.52	32	55
Leeds-Bradford	0.625	1.409	+125	1.74	1.35	21	38
Cardiff	0.487	1.250	+157	1.19	1.73	26	43
Liverpool	0.333	0.932	+180	0.59	0.94	12	27
Teesside	0.291	0.670	+130	1.05	1.10	19	39
Humberside	0.103	0.434	+321	0.98	0.96	35	40
Norwich	0.162	0.329	+103	0.97	1.04	17	66
Exeter	0.121	0.249	+106	0.96	0.98	20	45
Bournemouth	0.122	0.355	+191	1.08	1.10	39	32
Blackpool	0.140	0.087	-39	0.90	0.88	35	61
Southend	0.121	0.005	-95	N/A	1.02	N/A	20

Despite the different ownership structures, a general trend of traffic growth, financial self-sufficiency, increased emphasis on commercial revenue, and increased focus on marketing activity has been evident across the 16 airports since their commercialization in 1987. Municipal airport traffic grew more than 100 percent between 1986–87 and 1998–99 with only the two smallest airports in terms of passenger traffic suffering a decline (Table 1). Significant improvements in utilization levels may have been responsible for improved commercial and financial performance at the 11 smaller airports (defined by those with less than 1 million passengers in 1986–87). Previous studies have revealed that costs of airport operation per passenger fall dramatically until a critical mass of 1 million passengers per annum is reached (*23*).

Airport revenue is derived from charges to airlines (operational sources) and income from rents, concessions, and retail activities (commercial sources). The share of revenue generated from commercial sources is determined by the level of aeronautical charges, the traffic base, the availability of land for development, the size and design of the terminal building, and the skill of management to exploit the airport's commercial potential (*23*).

The Airports Act was successful in its attempt to introduce more commercially focused management at airports. Revenue from commercial activities grew at all the airports except Bournemouth, irrespective of size and traffic base between 1986–87 and 1998–99 (Table 1).

Of the 15 airports reported in studies by the Chartered Institute of Public Finance and Accountancy (CIPFA) (*22, 24*), the vast majority (87 percent) experienced a growth of commercial income above 15 percent of total income. The number of airports with more than 30 percent of their income from commercial sources rose from 40 percent to 100 percent between 1986–87 and 1998–99. An increase in marketing activity since 1986 is further evidence of the new commercial focus adopted at airports. Before 1986, marketing seldom involved more than press releases issued from the offices of the airport's municipal owners (*25*). By 1992, the majority of airports had created marketing departments. By 1998, the numbers employed per passenger handled had risen, and activities such as pricing to attract airlines, promotional campaigns, market segmentation, and market research had become commonplace (*26*).

Airport profitability is best measured in terms of the financial assets employed in the business; however, it is difficult to establish the real asset values of airports. An alternative approach is to use the revenue/expenditure ratio (revex ratio), which is the total revenue expressed as a ratio of the total costs after depreciation and interest and before tax (*27*). Depreciation and interest are not included in the revex figure in order to make the data comparable over a period when accountancy practices altered at many airports.

The revex ratio remained similar at airports with under 1 million passengers per annum in 1998–99 apart from Liverpool, where a considerable improvement was made. Airports with more than 1 million passengers in 1998–99 were all profitable but were split evenly between those that had an improved revex ratio and those where a decline was recorded (Table 1). The increased cost of operation due to the introduction of major development can explain the fall in revex ratio at Manchester (new terminal and new runway), Birmingham (new terminal), Newcastle (added terminal capacity), and Leeds-Bradford (a runway extension). In all, it does not appear that the Airports Act made any significant difference to profitability. The key difference has been that airports have maintained profitability despite having to self-fund development. It is unclear how much this performance has been due to traffic growth and how much it was due to ownership.

How have the airports that were commercialized, but have remained in public-sector ownership, performed in their own right and relative to airports that have changed their ownership structure? This question is considered in the following sections.

Public-Sector Airports

Around half the commercialized airports in the U.K. have remained in the public sector (see Figure 1). In response to the postal survey, Leeds-Bradford, Luton, Manchester, Newcastle, Norwich, and Teesside all expressed the view that their airports should be owned

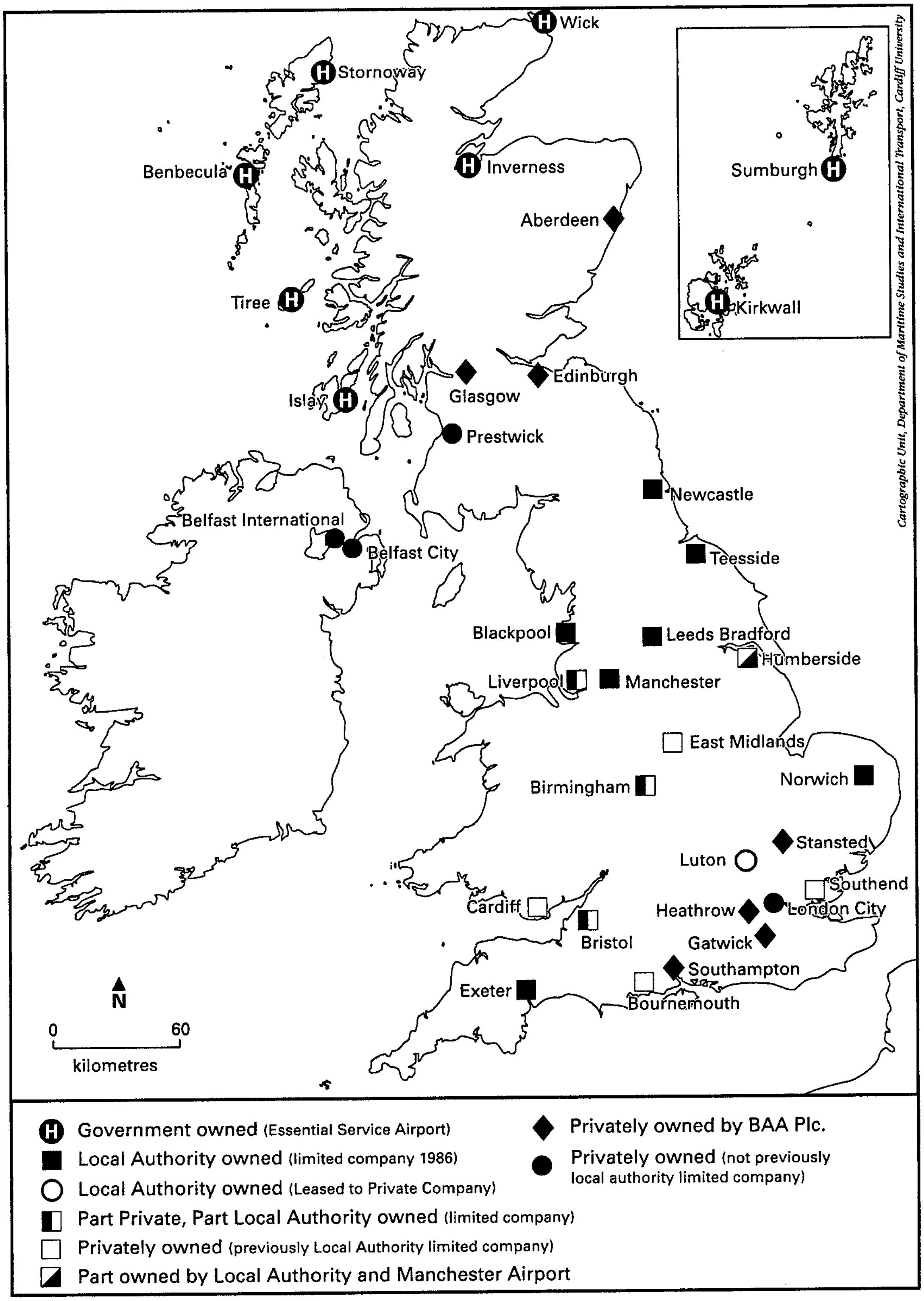

FIGURE 1 Ownership structure of U.K. airports, 2000 (Source: Individual Airports).

and operated by the public for the public good. A manager from Manchester stated, "In our view, privatization could not have produced a better track record and would probably have reduced many of the benefits the airport generates." Newcastle echoed these views. The benefit of keeping Manchester airport public is the preservation of the annual financial contribution that the airport makes to its local authority owners, a factor that helps to reduce local taxes and supports local public services. If the airport had been sold to the private sector, then any benefits from revenue generated would go straight into the pockets of the private owners. These local authorities are keen to retain an asset that returns a profit after years of subsidy from the public purse throughout the 1960s and 1970s. Whether or not performance would have been even better under a different ownership structure is difficult to prove one way or the other.

Manchester has lowered aviation charges, and Newcastle, Luton, Leeds-Bradford, and Teesside have offered discounts for new routes in an attempt to attract more air services (*28*). Management has developed retailing within the terminals and has undertaken various business activities to maximize the commercial revenue potential of their airport sites (Table 2). Manchester has developed hotels and office space, has won a management contract for two Australian airports, and has developed terminal capacity in a joint venture with British Airways. In 1999 the first example of a publicly owned airport being free to acquire another came to light when Manchester was allowed to take an 82.7 percent stake in publicly owned Humberside airport. Initial plans include development of a business park and a terminal upgrade.

Initiatives have also been taken at the smaller publicly owned airports. For example, Norwich has started a travel agency business and leased land for hangar space and for an airline reservation center. Significantly, Norwich took the financial risk and successfully operated flights to holiday destinations when the airlines refused to offer services. Normally small airports are at the mercy of airline decisions, yet financial freedom has enabled the airport to successfully take control of its own destiny (*29*). Teesside put forward plans in 1997 to develop a 100-ha (250-acre) airport site for various commercial uses in partnership with Schiphol airport and a property developer (*30*).

A new form of public ownership emerged at Luton in August 1998. Luton has ensured that the £170 million development of the airport is accomplished without giving up any equity through an agreement whereby a 30-year concession to operate and develop the airport has been won by a consortium made up of Barclays Bank (65 percent), TBI plc (25 percent), and Bechtel Enterprises (10 percent). The local authority maintains oversight through the terms of the concession agreement and receives an annual income from the concessionaires, part of which is related to profits (*31*). This may provide another model for authorities that wish to maintain full ownership and fund expansion.

TABLE 2 Selected Publicly Owned Airports

Airport	Business Activities
Manchester	New runway and terminal
	Discounted landing fees
	Increase retail
	Develop hotels and offices
	Environmental partnership with community
	Lobby government to lift borrowing restrictions
	82.7% ownership of Humberside
	Offer airport consultancy services
	Management contracts at two Australian airports
	Development of business park
	Joint venture with British Airways
Newcastle	Contracting out of baggage handling and other services
	Increased retail
	Discounted landing fees
	Growth in marketing department
	Terminal extension
Norwich	Lease land - hangars and reservations center
	Travel agency business started
	Air service operated
	Retail increase
Luton	Run as concession
	Attractive start-up charges for airlines
	New terminal and parkway station
	Increased retail space
	Travel agency
	Hotel and office development

Source: Survey data and interviews.

Until April 1999, access to the private financial markets was not possible under full public ownership, and the pace of expansion at public airports was slowed or in some cases totally constrained by the need to finance from their own revenue stream. New government rules freed publicly owned airports to borrow money from commercial markets. This was a crucial policy development in terms of access to finance for expansion because it removed a major incentive for privatization (*32*). Manchester, Leeds-Bradford, Newcastle, and Norwich have been financially cleared to borrow from the commercial markets.

Public-sector airports appear to have developed commercial sources of revenue, diversified their businesses, improved customer focus through marketing, and exploited the airport site. All are financially self-sufficient and do not depend on public money for their development.

Full and Part Privatization of Airports

Under the terms of the Airports Act, local authorities could sell their shares to the private sector. Cardiff, East Midlands, Bournemouth, and Southend have all privatized (see Table 3). The first three could not fund development from their own revenue streams and so have privatized to gain access to finance for expansion. Privatization has freed the public from subsidizing loss-making Southend but has diverted the profits from the local authorities that owned Cardiff, East Midlands, and Bournemouth to the new private owners in exchange for the purchase price. The full implications of privatization for these airports will become evident only with the passage of time; however, some preliminary implications are presented in Table 3.

One particular outcome of privatization at Cardiff, discovered through the postal surveys and referred to on a site visit, is worth further consideration. The firemen have been trained to handle baggage and assist with other operational tasks. This multitasking was introduced to increase the contribution of the firemen to the operation of the airport during periods when they may have little to do. The same has happened at Sheffield City airport, a new privately owned airport in the North of England. Interestingly, the head of the fire service at Sheffield claimed that the multiskilled role had given the firemen a better appreciation of the context of their workplace, particularly in terms of increased familiarity with aircraft operations and interiors.

Similar trends in activities have prevailed at airports that decided to sell only part of their shares to private owners (see Table 3). The important difference is that partial privatization has maintained some of the financial rewards for the public sector and a degree of direct control while providing access to finance for development and without total forfeit of the financial rewards to the private sector.

In summary, this section has shown how airport commercialization removed the burden on the public sector of borrowing to fund airport development. Evidence from the municipal airports reflects the general argument in the literature that there is "considerable doubt" that private-sector ownership is more efficient than public-sector ownership (*15*, p. 477). The principal impact of privatization in the U.K. appears to relate to commercial activities at airports rather than traffic

TABLE 3 Fully and Partly Privatized Airports

Airport (Buyer/Price £M)	Reason for Sale	KEY Business Activities
Privatized Airports		
East Midlands (National Express 1993/£40M)	Access to finance for expansion Owners required the money to avoid deficit	£70 million DHL Hub attracted Aircraft handling fees reduced Pursuit of Airport management contracts worldwide Development of Business Park Maximize revenue from Airport Land £30M planned investment
Cardiff (Thomas Bailey International 1995/£37.5M)	Access to finance for expansion Local Government re-organization in Wales	Purchase of 22 Travel Agents TBI Airports Group own/manage 40 airports Operation of air services Retail floor space trebled £7 million terminal development completed £20M planned investment
Bournemouth (National Express 1995/£7.2M)	Access to finance for expansion	Development of revenue from land assets Planned investment of £2M
Southend (Regional Airports Ltd 1994/Undisclosed)	Survival in the face of bankruptcy	Buying electricity in bulk and selling it on Focus on revenue from land assets Developed a Business Park £1M Planned Investment
Part Privatized Airports		
Liverpool (BAe 76% 1990£22M 1997 Peel Holdings 76%)	Survival	Contracting out strategy (only 6 employed) at one point in 1997 Developed lo-cost market Develop direct holiday market
Birmingham 1995/£130M (2000 Aer Rianta + NatWest 48.5%, Council 49%)	Access to finance for expansion	Previously expanded through getting BA to invest in Eurohub terminal Ideological move
Bristol (Firstbus 1997/£40M)	Access to finance for expansion	Contracting out Fuel/Ramp Handling/Car Parks/Cleaning

Source: Survey data and interviews.

growth or even improving finances (*3, 15, 33, 34*). Other than increasing revenue for airport companies, this does not necessarily imply any positive transport infrastructure benefits. The next section reflects on this and examines what lessons, if any, the United States could draw from the various models adopted in the United Kingdom.

DISCUSSION OF LESSONS FOR COUNTRIES CONSIDERING PRIVATIZATION AND COMMERCIALIZATION

This section considers what policy makers might learn from U.K. experiences when considering moves toward greater privatization and commercialization. What alternative ways are there for the United States to fund the massive investment required for U.S. airport infrastructure to be able to accommodate forecast traffic increases? What lessons could be learned from the models that have emerged from the 14 years of experience in the U.K.?

There are three main potential benefits of privatization in the United States, according to advocates of this policy. It is argued that private airport owners can make airports more profitable and productive, that they can introduce the necessary capital for development, and that they will thus relieve the financial pressure on the state for funds and increase the tax base (*4*, p. 5, *35, 36*). Opponents have argued that private airports could exploit their monopoly power and overcharge airlines, which may then pass on increased costs to the consumer. Loss of public funds, fears that private firms would divert profits from airport investment, and implications for the environment are further concerns that have been expressed. The main barriers to privatization cited include legal questions about renegotiations of existing airport-airline relationships and whether or not local and state governments would be allowed to keep the proceeds if they sold their airports (*4*, p. 6, *37*). What light does the U.K. experience shed on some of these issues?

Privatization and commercialization are economic forces that are unlikely to disappear. With the need for large-scale investment in airports, the question becomes what form of ownership will be adopted to pay for it, given that on the whole the need to make continual capital investments in the U.S. airports is not disputed (*8*). An important driver for change is the extent to which the public can be expected to finance the projected cost of airport development. The strong U.S. public service ethos will not stop change if airport congestion, delay, and restrictions on further service provision begin to constrain the nation from going about its daily business. There is an economic price to pay for not expanding U.S. airports.

Given the importance of this issue, debate should be taking place about what form the private investment should come in and how new ownership structures should be regulated to protect U.S. national economic and environmental interests. Looking at U.K. experience from the municipal airports, it appears that commercialization of airports, but with ownership maintained in the public sector, would be an attractive model, given the pro–public ownership views evident thus far in the U.S. context. To assess the implications of privatization further, in 1996 the FAA made available five slots for airports to take part in a pilot program. To date, the only airport to privatize under this process is Stewart International, taken on a 99-year lease by National Express, owners of East Midlands and Bournemouth airports in the U.K. (*37*).

Those airports that have remained in local government hands in the U.K. show that airports can behave in a commercial manner, develop to meet the challenges of demand growth and expansion without cost to the taxpayer, and remain under public ownership. In short, the public finance that helped to develop the airport when the air transport market was not so lucrative can now offer benefits to local taxpayers in return for their funding of the airport through lean development years.

Most U.K. airports cited access to finance as their main reason for full or part privatization. A key piece of U.K. legislation that enabled public airports to borrow from the private markets became effective in 1999 and in doing so gave them the means to finance development. Before this legislation, development had been constrained due to lack of access to capital. Access to capital markets should be granted and regulated if airport development is to be encouraged and not constrained.

Parker showed that U.K. airports were being no more efficient in the private sector than they were in the public sector (*1*). Many of the productivity gains cited by proponents of full privatization in the United States (*4*) have been evident at the municipally owned commercialized airports in the U.K. The ownership model at Luton—a public authority offering a concession to manage and operate the airport—is one that is currently proving a success at Indianapolis where BAA plc has a management contract that is reported to have generated increased income for airlines, the owners, and the BAA plc itself. Such a model offers public control, removal of the financial burden of development, and increased profits, although these are shared with the private sector (*37*).

The U.K. case shows that airports of different sizes can break even—not just the larger airports but the smaller ones, too, which traditionally were believed to be unprofitable and unable to pay their way. This is a particularly significant finding for the United States because of the large numbers of small and medium-sized airports that are forecast to suffer a 50 percent funding shortfall (*14*). The part-privatized U.K. airport ownership model offers public control of the airport but with access to private finance for development. The performance of these airports was not particularly different from that of airports that remained fully public. The key point of differentiation is that a share of the profits has been lost to private shareholders. It is important to note that this ownership form has not been pursued since municipal airports have been permitted to borrow from the private financial markets.

The fully privatized U.K. airports perhaps show a greater degree of diversification in commercial activities than public airports (with the exception of Manchester airport), driven by their need to maximize shareholder value. Fortunately, in the main, the interests of private shareholders and the public have overlapped because the commercial development of an airport brings more revenue to shareholders, more jobs, and greater numbers of air links for the community. This coincidence of purposes may not always continue to be the case (*38*), particularly if shareholders can make higher returns on alternative activities.

The fear of adverse effects due to the shareholder focus of private airport companies could be eliminated if U.S. airports were commercialized but kept in municipal ownership. If this were the case, the local authority could maintain control, a fact that should guard against the privatization fears of misuse of the airport site, environmental externalities, closure, and redevelopment (*35*). Maintaining local authority ownership is one way to ensure the owners act in the best interests of the wide variety of stakeholders because they are politically accountable. As a precautionary measure, regulation may be needed to make the planning system transparent when the local authority owners are also the planning authority. However, such ownership does carry with it the concomitant financial risk.

Within the U.K. context, the nature and form of airport regulation and its consequences have become increasingly significant (*3*). The government took a "golden share" in BAA plc to maintain a degree of potential control; it capped aeronautical charges and regulated accounts. A review of the FAA's regulatory role would be needed to maintain the protection of public interests. Part of the strength of the U.S. national planning system is the control over development that central funding permits. This must be guarded by regulation if commercialized airports that were no longer dependent on the public purse were permitted. The federal government potentially could maintain a "golden share" in each commercialized airport to guard against conflict with national interests.

Governments need to seek to understand the appropriate application of regulation in order to protect the interests of the public. The role of regulation will be crucial because regulation is one of the few policy levers that remain for governments to guide this dynamic industry, with all its economic and environmental implications. Airports do enjoy a degree of spatial monopoly that does need regulating in the interests of the consumer. A wider stakeholder view of such regulation is required, however—one that is consistent with wider policy goals and the implications for society as a whole.

It is important to acknowledge that not everything about the U.K. practices should be regarded as optimal. For example, price capping of airport charges has brought conflicts with the wider U.K. environmental policy by making the busiest and most congested airports among the cheapest to land at. Also, there has been no national plan in the U.K. to guide development in the economic and environmental interests of the country (*39*). However, this does not mean that there are not important lessons to be drawn from the experience described. These lessons may illustrate how not to do things as well as provide a model of best practice that can be benchmarked.

CONCLUSIONS

Commercialization of the main U.K. municipal airports and the privatization of the BAA under the 1986 Airports Act have removed the financial burden of airport operation from the U.K. government. The experience of allowing the commercialized U.K. municipally owned airports to borrow private funds would appear to offer all the financial benefits advocated by proponents of airport privatization in the

United States while guarding against the possible negative outcomes. Removal of such a financial burden from the state, potential increase of the tax base, and improved commercial performance could be achieved with protection against loss of control, monopoly abuse, and diversion of funds. To make this a reality in the context of another country, the form and nature of regulation will need to be developed to safeguard the full range of stakeholders.

Given the size of the investments required to accommodate forecast increases in traffic, governments around the world may no longer be able to afford to own airports. The U.K. example provides an indication of some of the alternative courses of action and their consequences, but this is not the only available model for governments to adopt. It is the authors' contention that appropriate regulation complemented by a coherent policy framework of goals that reflect the economic and environmental needs of a country is required to guide privatized and commercialized airport development.

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Measuring the Level of Services at Airport Passenger Terminals

Comparison of Perceived and Observed Time

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A mathematical model to measure the level of service at airport passenger terminals is presented. The model relates passengers' ratings of services at terminals and the time spent waiting for those services. The fuzzy concept is used to deal with the vagueness of service ratings such as "satisfied" and "unsatisfied." Furthermore, two instruments are used to obtain the amount of time spent in service processes: perceived time reported by passengers and objective quantities measured by researchers. Empirical data reveal that the mean of perceived waiting/service time is significantly greater than the objective time in both check-in and baggage-claim processes, indicating that passengers tend to overestimate their time spent in each process. Furthermore, the amount of overestimation varies among service processes, with passengers having greater overestimations in both check-in service and baggage-claim waiting than in check-in waiting. These results imply that the two former processes are less tolerable than the latter one. The differences between those two measurements are further accentuated by the estimated level-of-service thresholds, with most thresholds based on subjective perceptions being greater than those based on objective measures. Estimation results also suggest that airport operators and airlines need more efforts to upgrade a service currently at higher service levels than at lower service levels.

An airport may be divided into two components based on different activities: airside and landside. Airside is directly related to aircraft operations, including aprons, taxiways, runways, air traffic control systems, and other navigation facilities. Landside may be defined as the area at which passengers enter or leave the airport, enplane and deplane, and incur necessary processes for departure or arrival such as check-in, security check, and baggage claim. In general, landside consists of airport access roads or other modes of public transportation, parking lots, and facilities at passenger terminals.

Airport operations involve four major groups of actors: users, airlines, airport operators, and other concessionaires. Each group has its own specific objectives and interests. For example, airlines are interested in safety and profits; airport operators are concerned with regulations, safety, and revenues in some cases; and passengers want to have comfortable and convenient services. Nevertheless, the main objective of an airport is to provide services for its primary customers, the passengers. As it becomes more and more prevalent for airports to adopt the customer-oriented service concept in airport management, it is necessary to measure an airport's services from the passenger's point of view, which is exactly the intent of this study.

Specifically, this study aimed at setting up a measure of the level of service with respect to each process at airport passenger terminals. It is well recognized that the measure should be based on passengers' perceptions of how much time they incur in waiting or being served at each process, and how they feel about the waiting or the service. On the other hand, airport operators and airlines might be interested in obtaining the exact amount of waiting/service time, as the objective quantity is easier to define and measure. Therefore, improvement goals can be more clearly set. Because both subjective perceptions and objective measurements are essential in understanding how airport terminals perform, both sets of information were obtained simultaneously from a specific sample of passengers at airports. Furthermore, an in-depth analysis of data from different instruments will enrich the knowledge of the level-of-service measures at airports, which, in the past, were studied only on the basis of either perceived information or objective data.

It is essential to define the level of service at airports in airport terminal planning, design, and operation, though few efforts have been made on formally modeling airport landside services. To shed light on this area, a quantitative model to define the level of service at airport passenger terminals also is presented. The model uses the fuzzy concept to relate subjective service ratings to time measurements of associated waiting or service processes. Estimation results are further investigated to draw empirical implications for airport operators, airlines, and other practitioners.

Literature related to services at airport passenger terminals is provided in the following section. The third section contains the methodology of this research, including a survey design to simultaneously obtain subjective service ratings, perceived and objective time measurements, as well as the conceptual development of employing the fuzzy concept to measure the level of service with respect to each process. The empirical results are discussed in the fourth section, including both the explanatory statistical analysis and the estimation of the level-of-service models. The last section concludes with empirical implications and some further research topics.

BACKGROUND REVIEW

The work on the capacity and level-of-service measures of airport terminals can be grouped into three approaches: manual approach, queuing theory approach, and user perception approach. In the first group, the concept of airport terminal design is adopted from highway transportation with the so-called 30th highest hour volume. There are different forms of design criteria such as the typical peak hour passenger used by the FAA, the standard busy rate used by the British Airports Authority, or the planning peak hour passenger used by Transport Canada (*1*). The limitation of this approach is that the design criteria

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are set by airport planners, and often without considering perceptions from the major airport users: passengers.

In the second group, queuing models are used to evaluate the performance of an airport. A typical study can be found in McKelvey (*2*), with the airport passenger terminal represented as a queuing network in which a unit of demand enters the queue and service is performed. The model uses average waiting time and service time as indicators to evaluate the performance of various processes at airport passenger terminals.

According to the third approach, the acceptable amount of waiting/service time in each process is decided by passengers. This acceptability is defined as different service levels from passengers' viewpoints. Passenger surveys are typical vehicles used in this approach to obtain passengers' perceived waiting/service time and their subjective ratings about the waiting or service. Ashford (*3*) as well as Mumayiz and Ashford (*4*) used a graphical method to relate the levels of service (subjective ratings) and waiting or service time reported by passengers. In this study, passengers at airport terminals were asked to rate each service from three levels: good, tolerable, and bad. The response percentage for each level was plotted against time spent in each facility (also reported by passengers). Level A, or good, was defined as the time interval in which the "good" curve exceeds the "tolerable" curve. Level C, or bad, was defined as the interval in which the number of "bad" responses exceeds the number of "tolerable" ones. Level B, or tolerable, was defined as the interval between these two limits. Ndoh and Ashford (*5*) also proposed a framework to evaluate the level of service at airports using fuzzy sets and illustrated by a set of artificial data and simplified discrete membership functions.

Yen (*6*) adopted the same idea suggested by Ashford (*3*) and conducted a survey at the municipal airport of Austin, Texas. Unlike Ashford's graphical method, Yen applied logit models to estimate a "long" model and a "short" model to predict the probabilities that a passenger will rate a service on the basis of perceived time measures. The long and short models were then used to build a mechanism to define different service levels. The advantage of Yen's model is that it measures the level of service at airport passenger terminals on the basis of a well-defined behavioral model and has the capacity of forecasting.

No research in the literature to date has made an effort to investigate the relationship between perceived waiting or service time reported by passengers and objective measures by researchers. This study explored this issue by conducting a survey to obtain both sets of information simultaneously from airport terminals.

METHODOLOGY

Survey Design

In order to reach the research goals of developing a mechanism to measure the level of service at airport terminals and comparing results from different measurements, three sets of information have to be obtained from each sampled passenger. The first consists of a subjective rating based on the passenger's experience in waiting or being served in each process of interest. The second is the perceived waiting/service time, as reported by the passenger. The third is the actual waiting/service time incurred by the passenger and measured by researchers using objective instruments. Questionnaire survey and videotape recording are designed to obtain those three pieces of information from each individual, with the former eliciting subjective ratings and perceived waiting or service time and the latter measuring actual time spent in waiting or under service. Processes related to passenger departure and arrival at airports are measured.

For departure processes, passengers were asked to fill out a questionnaire in the departure lounge while they were waiting for a flight. The questionnaire contains three major parts: (*a*) trip characteristics such as trip purpose and the number of luggage, (*b*) socioeconomic characteristics of the respondent, (*c*) perceived waiting or service time in each process incurred by the passenger and his or her associated subjective rating of the waiting or service. The subjective rating system is based on the Likert's five-scale and bipolar measure with scales from very satisfied, satisfied, neutral, unsatisfied, to very unsatisfied. With respect to arrival processes, due to the relatively congested environment and the passenger's eagerness to leave the airport, passengers were asked to mail back the questionnaires that were handed to them at the baggage-claim area.

To further compare the difference between perceived waiting or service time and actual time spent by passengers, videotape recording was also conducted in front of the check-in counters and the baggage-claim facilities to measure the amount of time that each passenger incurred in waiting and being served. Video recordings were done before the questionnaire survey was conducted in departure lounges to facilitate better matching of those passengers recorded on tapes and surveyed by questionnaires. After the survey, each respondent from the questionnaire collected was matched from recorded videotapes, and the associated actual waiting/service time was obtained by reading the clock shown on each tape. As a result, for each surveyed passenger, the actual time he or she spent in a specific process, his or her perceived time, and his or her subjective rating of the waiting/service were obtained. These data provide a unique opportunity to compare the service measures of various processes at airport passenger terminals based on different measurement instruments. In addition, the data can be used to estimate the proposed level-of-service measure model that mathematically relates subjective ratings to quantitative time measurements.

Measuring the Level of Services with Fuzzy Concepts

The Fuzzy Concept

Fuzzy set theory was first proposed by Zadeh (*7*) to deal with "an individual's subjective notion of a vague class" (*8*) such as "tall people" and "good services." By Zadeh's definition, a fuzzy set is characterized by a membership function that maps each point in its domain to a real number, labeled as membership grade, in the interval [0,1] (*7*). Similar to the ordinary crisp sets, the operation rules such as intersection and union as well as the arithmetics of the fuzzy sets have been well developed by Zadeh (*7*).

Recognizing that the perception of delay such as "satisfied" or "unsatisfied" is a subjective attribute rather than an objective one, the fuzzy concept is used here to interpret passengers' subjective ratings of waiting or services incurred at airports. In the specific topic of the present research, fuzzy sets define the passenger's subjective notion of his or her rating associated with each waiting or service, and membership functions map waiting/service time to the respective membership grades of the notion sets.

Applying the Fuzzy Concept to Measure the Level of Services

One of the main objectives of this research is to develop a new model to better measure the level of services of various departure and arrival processes at airports. As mentioned in the previous section, respondents were asked to subjectively rate each service from five possible items: very satisfied, satisfied, neutral, unsatisfied, and very unsatisfied. Each item is similar to a notion expressed by "natural language" and is considered a fuzzy set with a specific membership function, as represented in Equation 1.

$$A = \{[x, \mu_A(x)] \mid x \in X\} \tag{1}$$

where

A = a fuzzy set that represents a vague concept such as "satisfied" in this research,

$\mu_A(x)$ = membership function of A with respect to variable x, and

X = the domain of x.

In the specific topic of the present research, x is defined as the waiting or service time of a process incurred by passengers at airport terminals.

The concept developed by Teng (*9*) in which the family of triangular membership functions is used to define the fuzzy sets of the five subjective ratings used in this research is applied in this paper. The triangular membership function (Equation 2) is used to define fuzzy sets of the middle three rating items—satisfied, neutral, and unsatisfied.

$$\mu_M(x) = \begin{cases} 0, & x \le a, c \le x \\ \left(\dfrac{x-a}{b-a}\right), & a < x < b \\ \left(\dfrac{c-x}{c-b}\right), & b < x < c \\ 1, & x = b \end{cases} \tag{2}$$

where $\mu_M(x)$ and x are defined in Equation 1, with M being one of the three middle ratings; additionally, a, b, c, d, e, and f are parameters to be determined.

Alternatively, the linear membership function (or a truncated triangular membership function) is used to define the fuzzy set of either very satisfied (VS) or very unsatisfied (VU), as in Equations 3 and 4, respectively:

$$\mu_{\text{VS}}(x) = \begin{cases} 1, & x = 0 \\ \left(\dfrac{d-x}{d}\right), & 0 < x < d \\ 0, & d \le x \end{cases} \tag{3}$$

$$\mu_{\text{VU}}(x) = \begin{cases} 0, & x \le e \\ \left(\dfrac{x-e}{f-e}\right), & e < x < f \\ 1, & f \le x \end{cases} \tag{4}$$

Defining the Thresholds of the Level-of-Service Measures

This research attempts to develop a model that can determine the thresholds of different service levels. Unlike the procedure applied in highway transportation in which subjective perceptions of drivers are not considered, both passengers' subjective ratings of the services and time incurred by passengers in waiting or under services are included in modeling the level of service at airport passenger terminals. Following the calculation of the five consecutive membership functions of service ratings (very satisfied, satisfied, neutral, unsatisfied, and very unsatisfied) as defined in the previous section, the thresholds can be estimated to mathematically set up the interval of each service level.

The thresholds are determined by taking the intersection of each pair of consecutive membership functions, if the intersection does exist. In addition, the five service levels (say A, B, C, D, and E) are defined by four numbers (x_1, x_2, x_3, and x_4) that represent the associated time coordinates of those four respective intersections. Service Level A is defined as "service or waiting time less than x_1," Level B is the time interval of (x_1, x_2), Level C is the interval of (x_2, x_3), Level D is (x_3, x_4), and Level E is the interval of "greater than or equal to x_4."

In case there is no intersection between two consecutive membership functions, the threshold is defined as the arithmetic mean of the extreme (right) value of the left membership function and the extreme (left) value of the right membership function.

EMPIRICAL RESULTS

The Sample

Empirical data were obtained from Chiang Kai-Shek (CKS) international airport, which is the major gateway of Taiwan and is located near the Taipei metropolitan. About 85 percent of international passengers flying into or out of Taiwan are served by CKS and the remaining by Kauhsiung international airport. In 1999, the passenger volume at CKS was about 17.7 million, including both origin-destination and transfer traffic.

The questionnaire survey and videotape recording were conducted in March 2000. In the departure processes, 62 passengers were surveyed and reconciled on videotapes. On the other hand, 84 arrival passengers mailed back their questionnaires, and 36 of them were reconciled on videotapes. Among the departure sample, about 60 percent of the respondents are male, and 61 percent of them have annual household income above the national average for Taiwan (1.07 million New Taiwan dollars, equivalent to U.S. $34,500). With respect to the arrival sample, about 47 percent are male, and 50 percent have household income above the national average.

Trip characteristics were also obtained from the questionnaire. Among departure passengers, 40 percent of them reported as "business" trips, and about 71 percent carried more than one piece of luggage. Similar to the departure sample, about 37 percent of the arrival passengers are traveling for "business" purposes. Arrivals, however, tend to carry more luggage than departure passengers, with about 88 percent of the former having more than one piece of luggage.

Statistics of the Data

Comparison of Perceived and Actual Time

Although the characteristics of a variety of processes were asked in the questionnaire, only check-in and baggage-claim services were recorded to measure associated waiting or service time actually incurred by passengers. Hence, only results of these two processes are listed in Table 1 to compare the differences between waiting or service time perceived by respondents and measured by researchers.

A comparison of those three measured items—check-in waiting time (CWT), check-in service time (CST), and baggage-claim waiting time (BWT)—reveals some rather interesting results. Based on actual time measurements, CST has the least mean whereas BWT has the largest mean. Nevertheless, when the comparison is made on the basis of the perceived amount of time reported by respondents, CWT has the least mean whereas BWT still has the largest mean.

In any of the three measured items—CWT, CST, and BWT—the mean of perceived time spent on waiting or on the service process is

TABLE 1 Statistics of Perceived and Objective Data

Process/measurements		Mean (min)	Coefficient of variation	Sample size
check-in waiting time (CWT)	actual	6.9	0.70	62
	perceived	9.1	0.83	62
check-in service time (CST)	actual	3.1	0.65	62
	perceived	10.6	1.17	62
baggage-claim waiting time (BWT)	actual	8.8	0.52	36
	perceived	15.7	0.64	36

always greater than the one actually measured by researchers through video recording. These results are further confirmed by a hypothesis testing on the difference between two respective means from paired observations, as listed in Table 2. The observations are paired in that for each process of interest two pieces of information (perceived and actual) are obtained from each respondent.

In Table 2, the mean difference $\bar{d}$ is calculated by taking the mean of differences between perceived and actual times from each individual with respect to each process, as shown in Equation 5. In addition, the standard deviation of the sampled mean difference $S_{\bar{d}}$ is equal to the standard deviation of the paired differences S_d, defined in Equation 6, divided by the square root of the sample size N.

$$\begin{aligned}\bar{d} &= \left(\sum_i^N d_i\right)\Big/N \\ &= \left(\sum_i^N T_{pi} - T_{ai}\right)\Big/N \qquad (5)\end{aligned}$$

$$S_d = \left(\sum_i^N d_i - \bar{d}\right)\Big/(N-1) \qquad (6)$$

where T_{pi} is the perceived waiting or service time and T_{ai} is the actual waiting or service time incurred by individual i with respect to each process.

The null hypothesis (H_0), versus the alternative hypothesis (H_A) in Equation 7 is tested to statistically compare the perceived time and actual time incurred in each process.

$$\begin{aligned}&H_0 : \mu_{T_p} = \mu_{T_a} \qquad (\mu_{\bar{d}} = 0) \\ &H_A : \mu_{T_p} > \mu_{T_a} \qquad (\mu_{\bar{d}} > 0) \qquad (7)\end{aligned}$$

The last column of Table 2 shows test results. In each process the t-value of the null hypothesis, stating that both means of perceived and actual times are equal, is greater than the one-side critical value at the 1 percent level of significance. The critical t-value is approximated by the z-value of the standard normal distribution ($Z_{0.01}$ = 2.33) due to a relatively large sample size ($N > 30$). This result rejects the null hypothesis and confirms that mean perceived time is greater than mean actual time in each process. Additionally, the coefficient of variation based on perceived time is greater than the one based on actual time in each process (Table 1), indicating that perceptive measurements have more deviation from their means than objective measurements. These results indicate that level-of-service measures are likely to be different if different measure instruments are used.

Analysis of Results

A closer investigation of the responses reveals interesting results, as illustrated in Figures 1 to 3. First, those three figures indicate that perceived responses related to waiting or service time tend to cluster on some integer numbers, unlike actual measurements that widely spread over the sample range. In addition, respondents are more likely to report integer numbers between 1 and 10 if perceived time is less than 10 min. Respondents tend to anchor in 5-min increments beyond 10 min of perceived waiting or service time. This may be attributed to the cognitive process and has a bearing on airport operations.

Specifically, the results imply that when perceived time is greater than or equal to 10 min for a specific process, an improvement of reducing waiting or service time by less than 5 min may not be easily identifiable by passengers. The thresholds of meaningful improvements may depend on current airport performances.

TABLE 2 Statistical Tests on the Difference Between Two Means from Paired Observations

Items	Mean difference for paired observations ($\bar{d}$)	Standard deviation of paired differences (S_d)	Standard deviation of sampled mean difference ($S_{\bar{d}}$)	Sample size (N)	t-value
check-in waiting time (T_p-T_a)	2.2	6.4	0.82	62	2.7
check-in service time (T_p-T_a)	7.5	12.3	1.56	62	4.8
baggage-claim waiting time (T_p-T_a)	6.9	7.4	1.24	36	5.6

T_p = perceived time; T_a = actual time (in minutes).

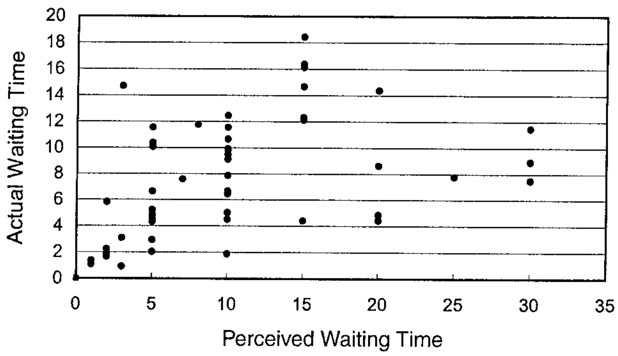

FIGURE 1 Perceived versus actual waiting time (in minutes) of the check-in process.

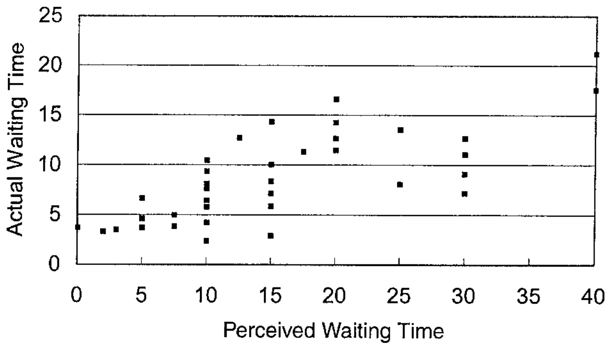

FIGURE 3 Perceived versus actual waiting time (in minutes) of the baggage-claim process.

Comparison of Processes

Statistical tests conducted in the previous section have shown that passengers tend to perceive more waiting or service time than what they actually incur in both check-in and baggage-claim processes. From the point of airport operations, it is also interesting to find out whether or not the amounts of overestimation among processes are statistically different. The combination of three processes studied in this research consists of three pairs of comparison: (*a*) difference between perceived and actual times in check-in service versus difference in check-in waiting, (*b*) difference in check-in service versus difference in baggage-claim waiting, (*c*) difference in baggage-claim waiting versus difference in check-in waiting. Table 3 lists the test results.

Mean tests are also used to determine the statistical significance. Because two pieces of information relating to check-in waiting and check-in service are obtained from each respondent, the test of item 1 in Table 3 is on the basis of paired observations as performed in Table 2. On the other hand, information on the check-in process and baggage-claim process is obtained from two independent samples. Therefore, tests of items 2 and 3 are treated as the comparison of means from two groups of independent observations.

On the basis of one-side *t*-test, the results of items 1 and 3 are statistically significant at the 1 percent level of significance ($Z_{0.01} = 2.33$). These results indicate that, on average, passengers tend to overestimate more in check-in service time than in check-in waiting time. Passengers also tend to overestimate more in baggage-claim waiting time than in check-in waiting time. Statistically speaking, there is no difference between the overestimations of check-in service and baggage-claim waiting. Using overestimation as an indication of intolerance, these results may imply that both check-in service time and baggage-claim waiting time are less tolerable than check-in waiting time. The different tolerances among processes may derive from the process itself and the environment where the process is executed. For example, the baggage-claim area is generally considered noisier and less orderly than the check-in area. For airport operators or airlines, these implications may suggest the priority of improvement projects that either actually reduce service/waiting time of the process or improve the environment physically or psychologically.

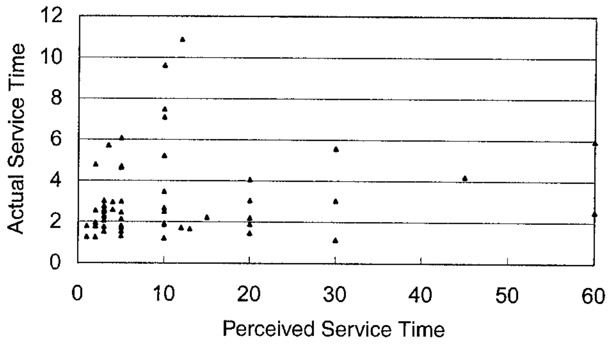

FIGURE 2 Perceived versus actual service time (in minutes) of the check-in process.

Estimation Results of the Thresholds of Different Service Levels

Time thresholds of different service levels are estimated using the fuzzy concept and are summarized in Table 4. The notations used in Table 4 are the same as discussed in the third section, with five service levels (from A to E) representing the corresponding five subjective service ratings (from very satisfied to very unsatisfied) and four numbers (x_1, x_2, x_3, and x_4) standing for the thresholds of different service levels.

As indicated in Table 4, all thresholds, except for x_1 and x_2 of CWT, based on passengers' subjective perceptions are greater than the ones based on objective measures by researchers, further confirming previous findings that level-of-service measures are likely to be different between user perception and actual observation. A comparison of the estimated time thresholds of those three processes listed in Table 4 indicates that CST has the least thresholds in both cases of perceived and actual time measures. This is also an indication that the process of check-in service is the least tolerable one, consistent with previous results as listed in Table 3. Interestingly, the comparison of CWT and BWT results in different conclusions, depending on the measurement instrument. On the one hand, the thresholds of actual CWT are higher than those of actual BWT, implying that baggage-claim waiting is less tolerable than check-in waiting, which is also consistent with results in Table 3. On the other hand, two out of three thresholds of perceived BWT are greater than those of perceived CWT.

Thresholds listed in Table 4 also provide important implications to airport operators and airlines. Recognizing that the actual amount of time airport operators or airlines have to improve in order to upgrade a specific process from a lower service level to a higher one depends on the current waiting/service status of the process, differences

TABLE 3 Statistical Tests on the Overestimations Between Two Different Processes

Items	Mean difference ($\bar{d}$)	Standard deviation of sampled mean difference ($S_{\bar{d}}$)	t-value
Difference in check-in service time (T_{pcst}-T_{acst}) vs Difference in check-in waiting time (T_{pcwt}-T_{acwt})	5.3	1.19	4.5
Difference in check-in service time (T_{pcst}-T_{acst}) vs Difference in baggage-claim waiting time (T_{pbwt}-T_{abwt})	0.6	1.99	0.3
Difference in baggage-claim waiting time (T_{pbwt}-T_{abwt}) vs Difference in check-in waiting time (T_{pcwt}-T_{acwt})	4.7	1.48	3.2

T_{pcst} = perceived check-in service time; T_{acst} = actual check-in service time (in minutes).
T_{pcwt} = perceived check-in waiting time; T_{acwt} = actual check-in waiting time (in minutes).
T_{pbwt} = perceived baggage-claim waiting time; T_{abwt} = actual baggage-claim waiting time (in minutes).

between any two consecutive thresholds may be used as indices of efforts that airport operators or airlines must make to implement associated improvements. To apply this concept, let d_{ji}, defined as $x_j - x_i$, be the index of upgrading the service from the jth level to the ith, with the first level being Level A (very satisfied) and the fifth level being Level E (very unsatisfied). According to the third row of Table 4, the indices (d_{43}, d_{32}, and d_{21}) of actual CWT are 2.1, 3.5, and 5.5, respectively. These results indicate that, on average, airlines need to improve their waiting time by one-half of 2.1 min to upgrade this process from D service level to C service level, one-half of 3.5 min from C to B, and one-half of 5.5 min from B to A. It is also interesting to note that indices (d_{43}, d_{32}, and d_{21}) of actual CWT are in an increasing order, which implies that more resources may be required for service upgrades at higher levels.

This conclusion also holds for the perceived waiting time of the check-in process, as listed on the fourth row of Table 4, and those two different measurements of the baggage-claim waiting process. With respect to the check-in service, indices d_{43} and d_{32} keep the same increasing tendency, with d_{43} greater than d_{32}. The increasing order does not hold for d_{21} in that d_{21} is less than d_{32}.

CONCLUSIONS

A model is presented to relate a passenger's subjective ratings of various services he or she incurs at airport passenger terminals and time spent in waiting or receiving those services. The fuzzy concept is used to model subjective service ratings, and two instruments that are used to obtain the time spent in the process: perceived time reported by passengers through a questionnaire survey and objective quantities measured by researchers through video recording at airport terminals.

Empirical data reveal that in each process the mean of perceived time is always greater than the one actually measured by researchers. In addition, perceptive measurements have more deviation from their means than objective measurements. These results indicate that the level-of-service measures are very likely to be different if different measuring instruments are used. Differences between those two measurements are further accentuated by the estimated thresholds of service levels in each process: most thresholds based on subjective perceptions are greater than those based on objective measures. These results may have significant implications for the validity of level-of-service measures conducted to evaluate performances at different

TABLE 4 Estimated Thresholds of Different Service Levels in Each Process

Service levels		A		B	C	D	E
Thresholds		0	x_1	x_2	x_3	x_4	f
Check-in waiting time (min)	actual	0	4.4	9.9	13.4	15.5	f
	perceived	0	3.4	9.2	14.5	18.5	f
Check-in service time (min)	actual	0	2.1	2.8	4.5	5.9	f
	perceived	0	3.6	6.2	10.4	12.2	f
Baggage-claim waiting time (min)	actual	0	--	7.4	10.5	13.2	f
	perceived	0	--	7.6	15.8	22.8	f

NOTES: The upper bounds "f" are not shown in the table.
Passengers seldom reported "very satisfied" rating in the baggage-claim process; hence there are only four service levels that can be identified.

airports. They may also have a bearing on research about the value of time saving in terms of measurement instrument issues.

A comparison of results from different processes revels that both check-in service and baggage-claim waiting are less tolerable than check-in waiting. This may suggest the ranking of the list of airport terminal improvement projects and hence the allocation of resources. Other interesting results emerge when surveyed data show the anchoring effect of perceived responses to each process and model estimations reveal the increasing order of the indices of necessary efforts from lower service levels to higher service levels. These results may influence the decisions of airport operators and airlines in terms of the trade-off between the amount of resources for service improvements and whether or not the improvement is meaningful in terms of perceived time and defined service levels. These are interesting research topics for both researchers and practitioners. One related topic may be the comparison of other services such as the customs examinations of arrival passengers, which are extremely enforced in some countries. This was not conducted due to the regulation that does not allow video recording at customs areas of the CKS airport.

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Near-Term Procedural Enhancements in Air Traffic Control

Wayne W. Cooper, Jr., Laurence M. Gordon, Bradley T. Hargroves, David R. Maroney, and Joseph Spelman

As the National Airspace System (NAS) of the United States grows in usage and complexity, there is continuous improvement in the procedures that support it. Of particular interest are the improvements that can be made without acquiring new automation or systems. Fundamentally, these improvements are changes to the performance of operations that make better use of the tools and capabilities currently available to the users and service providers. These changes are collectively called "procedural enhancements." The Federal Aviation Administration (FAA) has identified a number of procedural enhancements that can be implemented in the 1998–2002 time frame, which has been labeled the "near-term" time frame. Due to financial constraints, not all the enhancements can be implemented, so FAA has selected several that could yield efficiency benefits to the NAS. In partnership with FAA, MITRE's Center for Advanced Aviation System Development (CAASD) is assisting with the implementation of several of these near-term procedural enhancements. These include lifting the 250-knot speed limit, improving North American Route Program transitions, reducing flow restrictions, and eliminating air traffic control preferred routes. Analysis and implementation of procedural enhancements by FAA and CAASD continue to assist system efficiency while new automation and tools are being procured.

There is an extensive series of initiatives by the Federal Aviation Administration (FAA) to improve the air traffic control (ATC) system in the United States. Many of these initiatives involve new automation capabilities or aides for the controller or pilot, while others strive to improve the infrastructure on which the system rests. However, while these improvements are being developed, a number of procedural changes are being introduced to provide efficiency benefits to the National Airspace System (NAS). These procedural changes are not associated with changes to systems or the introduction of new capabilities. Typically they are changes to how operations are performed today that make better use of the tools and capabilities that are currently available to the users and service providers. These changes collectively are called "procedural enhancements."

To establish the context for these improvements, the FAA Administrator's NAS Modernization Task Force identified several strategies (*1*) in late 1997 to provide measurable steps toward the RTCA, Inc., concepts of free flight (*2, 3*). One key strategy is to deliver early benefits to users by 2002, through the fielding of low-risk capabilities at specified locations throughout the NAS. This activity is entitled Free Flight Phase 1 (FFP1), consisting of the limited deployment of selected core air traffic management (ATM) capabilities (*4*). The intent is to deploy these capabilities, currently in development status or in limited operational use at some FAA facilities, to other facilities or locations as quickly as possible (to allow for evaluation by 2002) in order to provide early benefits to NAS users. This time frame (1998–2002) has been established as the "near-term" time frame.

Concurrently, in the near-term time frame of FFP1, FAA has identified a series of 25 procedural enhancements (*5*). These "near-term procedural enhancements" can provide rapid benefit to the NAS, can be made with relatively little expenditure of program funds or resources, and are fundamentally independent of the other near-term NAS initiatives, such as FFP1. However, due to financial constraints, not all 25 of the enhancements can be implemented in the near-term time frame. FAA has reviewed these procedural enhancements and is in the process of implementing those that have been judged to be most potentially beneficial to the NAS users.

In partnership with FAA, MITRE's Center for Advanced Aviation System Development (CAASD) is assisting with the implementation of several of these near-term procedural enhancements. CAASD's analytic and operational experts have helped with the design or redesign of procedures, the analysis of benefits and impacts, the evaluation of field trials, and the coordination of service providers and users. Four of these efforts are outlined, and the results and improvements to date are discussed. These include lifting the 250-knot speed limit, improving North American Route Program (NRP) transitions, reducing flow restrictions, and eliminating ATC preferred routes.

LIFTING THE 250-KNOT SPEED LIMIT

In response to a 1995 RTCA Task Force recommendation (*2*), FAA initiated a study of modifying Federal Aviation Regulation (FAR) 91.117 to change or eliminate the 250-knot speed restriction for departing aircraft operating below 10,000 ft within Class B airspace. FAA asked CAASD to evaluate the effects and potential benefits of lifting the 250-knot speed limit.

The first step in the evaluation process consisted of controller-in-the-loop laboratory simulations conducted at CAASD in 1996. These high-fidelity simulations modeled Dallas–Fort Worth, Texas, and St. Louis, Missouri, terminal airspace, with and without the 250-knot speed restriction in effect for departing aircraft, and employed teams of controllers from those facilities. No major safety concerns or appreciable increases in controller workload were discovered during the simulations, and as a result, FAA decided to go forward with a field test of the procedure. Houston terminal radar approach control (TRACON) was selected, and a field test was begun in the summer of 1997.

To provide a comprehensive evaluation of the field test, three areas likely to be affected by the modification of the speed restriction were identified: air traffic controllers; flight crews; and the environment,

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specifically in the area of noise. Several metrics to support the assessment of each area were developed, including controller and pilot workload, fuel and time savings, improvements in flight profile, and changes in noise profiles and community complaint frequency.

The preliminary evaluation of the ongoing field test at Houston provided partial validation of the operational feasibility of modifying or removing the 250-knot speed limit for departing aircraft only. The results of the preliminary evaluation were, for the most part, positive (*6*). Major findings included the following.

- The vast majority of controllers interviewed believed that it is operationally acceptable for departures to fly faster than 250 knots, below 10,000 ft, within Class B airspace.
- When authorized to do so, a substantial number of controllers removed the speed restriction for departing aircraft.
- Most of the controllers interviewed preferred to have the departure controller retain the option of removing the speed restriction. This remains the procedure today.
- There was no significant impact on controller workload resulting from the change in procedure during the period studied.
- Changes to departure speed and altitude profiles varied but in general seemed to conform to the anticipated result that aircraft would generally trade altitude for speed. As an example, the average MD-80 (without the speed restriction) attained higher speeds in the window between 2 and 4 min after takeoff, and crossed 10,000 ft roughly 5 nautical mi further downrange.
- There was an apparent increase in the number of aircraft operating below 10,000 ft, outside the lateral limits of Houston's Class B airspace, at speeds greater than 250 knots when higher speeds were authorized, as opposed to when they were not authorized.
- All pilots interviewed during the test agreed that it was operationally acceptable for departures to fly faster than 250 knots, below 10,000 ft within Class B airspace.
- There was a modest saving per individual flight: a typical flight (i.e., a B737-300 with 20,000-lb-thrust engines, 105,000-lb takeoff weight, and a 100-min flight time) would save 9.6 lb of fuel and 0.1 min of flying time.
- There was no significant noise impact (as defined by FAA Order 1050.1D, 1986) in the Houston area, and no noise impact perceived by the community surrounding the airports.

Before transitioning out of this work area in September 1998, CAASD recommended the formation of a joint FAA and industry working group that would review the program's status and make recommendations concerning the advisability of continuing or expanding the program. At this time, the Houston trial is continuing, and FAA is considering the extension of the program to the other TRACONs with Class B airspace that extend to 10,000 ft or higher.

IMPROVING ROUTE PROGRAM TRANSITIONS

In December 1998, FAA released Advisory Circular AC90-91C, North American Route Program (NRP) (*7*). The advisory circular replaces AC90-91B, National Route Program (*8*). NRP is now a joint FAA and NAV CANADA program that integrates the U.S. national route program and the Canadian equivalent. Under NRP, flights were required to file and fly departure procedures (DPs), Standard Terminal Arrival Routes (STARs), or published Instrument Flight Rules (IFR) routes within 200 nautical mi of the departure and destination airports. A recent advisory update (*9*) identifies 286 transition fixes on 69 DPs in 29 airport areas and 296 transition fixes on 118 STARs in 39 airport areas. NRP flights may now file and fly to and from these transition fixes in lieu of the 200-nautical-mi restriction. FAA intends to expand NRP to all major U.S. terminal areas. The initial advisory did not extend into the following centers: Anchorage, Alaska; Boston, Massachusetts; Cleveland, Ohio; Honolulu, Hawaii; Jacksonville, Florida; Los Angeles, California; New York; or Miami, Florida. The update extends the scope of the advisory into the Jacksonville, Los Angeles, and Miami centers.

The advisory lessens the restrictions on NRP flights within 200 nautical mi of designated airports. Consequently, NRP flights are now often able to fly user-preferred routes for longer distances than before. Because of the often-greater flexibility in route selection, NRP flights now have the capability of maintaining greater separation from non-NRP aircraft that are adhering to published routes.

CAASD has assisted FAA's Air Traffic Control System Command Center (ATCSCC) by assessing the operational effects of NRP changes. Metrics analyzed include ATC sector counts, which represent the maximum number of aircraft within a sector during consecutive 15-min intervals. They are indicators of sector traffic congestion and controller workload. They were calculated using three-dimensional sector boundary data and flight track data from the Enhanced Traffic Management System (ETMS). Each sector's counts were compared with its monitor alert parameter (MAP), which is a dynamic integer value determined by FAA and indicates the number of aircraft beyond which sector efficiency may be degraded. When traffic within a sector is projected to exceed the MAP, the monitor alert function of ETMS sends an alert to traffic managers (*10*). Sector counts were calculated on busy traffic days before the advisory took effect, as well as 2 months afterward. No sector in the United States was found to experience a sector count increase over the MAP due to implementation of the advisory.

Due to the large number of terminal areas affected and the significant shift in many transition points, potential user flying time and operating cost savings across the NAS can safely be estimated to be in the millions of dollars. In February 2000, as part of a recommendation to FAA on additional NRP transitions, CAASD estimated the potential yearly NRP fuel cost saving at just seven airports to be more than $250,000. This estimate assumed no increase in NRP traffic and a jet fuel cost of $0.60 per gallon, which has increased dramatically since that time. The seven airports were Atlanta, Georgia; Charlotte, North Carolina; Dallas–Ft. Worth, Texas; Los Angeles and San Francisco, California; Chicago O'Hare, and Washington Dulles. In April 2000, the FAA implemented 8 of CAASD's 11 suggestions for NRP arrival transitions at O'Hare. At that time, no suggested departure transitions were implemented at O'Hare, although the FAA is regularly updating the advisory.

In June 2000, CAASD met with representatives of the ATCSCC as well as Washington center and Washington Dulles airport to discuss CAASD's study of suggested NRP transitions at Dulles. Because many FAA en route centers now have teams of controllers and traffic management personnel investigating the redesign of their airspace, the suggestions have been incorporated within the larger investigation, which offers the potential for more widespread user savings in distance flown and fuel burn. Whether any particular NRP flight actually realizes a benefit depends on whether its departure and destination airports are covered by the NRP advisory, the filed route, and weather-related factors such as the winds.

Many DPs and STARs now contain multiple NRP transitions often located much closer than 200 nautical mi to the departure or arrival airport. The new NRP transitions on the Denver, Colorado, vector departure procedure are identified in Figure 1. Usually these transitions are located at the intersection of jet routes. If NRP flights continue to file these published routes, then the impact on traffic patterns should be minimal. If, however, they file unpublished en route sequences from or to these transitions, then the possibility exists for an increase in ATC workload to assure safe separation during peak hours.

REDUCING FLOW RESTRICTIONS

Over the past several years, FAA's ATCSCC has worked aggressively to reduce restrictions throughout the NAS. In particular, major steps have been taken to remove static restrictions and to carefully scrutinize restrictions passed back from one en route center to another. CAASD has worked with the ATCSCC to try to understand the effects of restrictions and evaluate the operational impact of eliminating specific restrictions.

In the past few years, very detailed case studies have been undertaken in Chicago, Atlanta, and San Francisco to understand the extent to which restrictions can be lessened. During calendar year 1999, an analysis was performed of the restrictions that are passed from Washington center (ZDC) to major airports in New York center (ZNY) due to en route congestion in ZDC. The ATCSCC is concerned that these south gate restrictions are having a serious impact on the New York metro airports' ability to launch departures and that they might be causing large delays at these airports.

The analysis of the ZNY south gate restrictions was performed based on 3 months of data (from December 1998 though February 1999) from a wide variety of sources. After a lengthy data reduction effort, numerous statistics and a series of regression models were used to try to explain whether the delays could be caused by the restrictions under investigation. This particular analysis showed the following.

- There were relatively few south gate restrictions (compared with the north and west restrictions). Less than 10 percent of the flights were restricted, except for 6 hr of the day when 10 to 20 percent of the flights were delayed. Most of the restrictions were very short (i.e., less than 15 min) ground delays.
- When the miles-in-trail (MIT) restrictions were in place, the additional delay due to the restriction was "in the noise" (typically 0 to 3 min). The average aircraft spacing through the restriction point was more than 50 percent larger than the MIT restriction.
- In general, for south gate departures, no relationship could be found between departure delays and the MIT restrictions. To the contrary, the largest average push-back delays to flights entering the concerned ZDC sectors occurred when there were no south gate restrictions (after 11 p.m. local time). It was estimated that the ground stops added an additional 5 to 8 min of delay.
- Aircraft counts in the concerned ZDC sectors do not reach the MAP thresholds as frequently as some other ZDC sectors. Traffic in these sectors came predominantly from the New York metro area, but traffic from Philadelphia, Baltimore-Washington and Washington National, and other nearby airports also was a significant factor when restrictions were in place.
- MIT restrictions do not appear to cause a significant increase in average taxi times for flights following restricted flights in the departure queue.
- During time periods when restricted southbound New York departures reach the key ZDC sectors studied, other departures from nearby airports entering these sectors (specifically Baltimore-Washington, Washington National, and Washington Dulles) were not usually restricted. However, a high percentage of Philadelphia departures are restricted during these times.

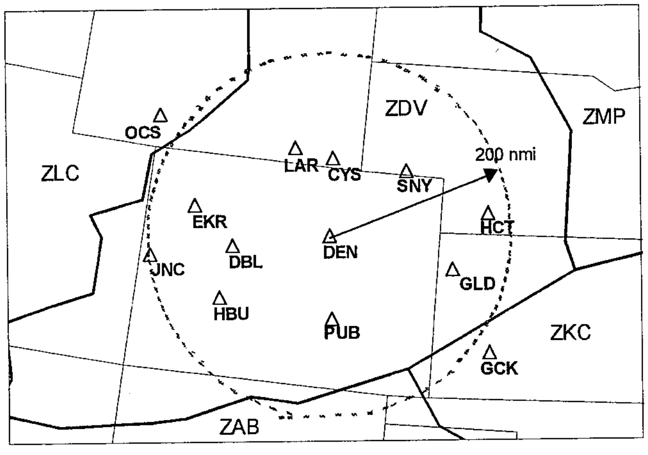

FIGURE 1 NRP transitions on Denver departure procedure (nmi = nautical miles).

Taken together, these results suggest that the need for these south gate restrictions must be called into question. As in prior restriction case studies, these results will be discussed with the affected facilities, and, where possible, agreement will be reached on the extent to which the restrictions can be reduced.

A thorough analysis of en route and departure flow restrictions that affected flights passing through Cleveland center (ZOB) was performed during calendar year 2000. The goal of this analysis was to provide quantitative metrics to decision makers in the ATCSCC that can be used to evaluate proposed historically validated restrictions (HVRs). An HVR is an MIT restriction that is put in place during specific hours of the day and days of the week by a facility. It must be approved by the ATCSCC before implementation. ZOB contains one of the most complex set of HVRs in the NAS, which have been put in place both to meter flights to control local-sector volume and to meter flights to meet downstream HVRs at the center boundary. About 85 separate HVRs affect ZOB traffic on a typical day.

Four days of flight plan data (from January 2000) were collected for the entire NAS. These data, representing the original user intent, were used to generate flight paths by the Collaborative Routing Coordination Tool (CRCT). CRCT is a prototype for an interactive suite of tools developed by MITRE to assist the traffic management units (TMUs) in a center to quickly evaluate the effect of proposed reroutes on sector MAP levels. For this analysis, CRCT was used to generate flight trajectories. The resulting trajectories were fed to the Detailed Policy Assessment Tool (DPAT), a fast-time simulation of individual flights in the entire NAS, which was used to simulate the movement of traffic through ZOB and the surrounding centers for the 4 historical days. The modeling and analysis were performed offline using archived data. Statistics were collected on the instantaneous aircraft counts versus the MAP for each ZOB en route sector and 15-min period. Delays also were estimated for each HVR modeled. Discussions are ongoing with the ATCSCC as to how to use this information to improve the current HVR approval process.

In addition to the offline modeling and analysis of MIT restrictions, a capability has been added to CRCT to model individual en route MIT restrictions. This is currently being evaluated as a potential real-time analysis tool to evaluate the use of MIT restrictions in the field before their implementation.

During the restriction case studies performed in the past several years, some common results and lessons learned have emerged.

- There is no complete knowledge on the level of restrictions in the system. Although the ATCSCC evaluates and logs the restrictions that are passed back across center boundaries, local restrictions are extensive and are not generally available for analysis. A substantial amount of effort is required to put these data into a format suitable for analysis.
- There is no good understanding of the true impact of restrictions (i.e., the amount of unnecessary delay caused). Extensive effort in modeling and data analysis has demonstrated how difficult this problem is.
- The use of and adherence to restrictions varies greatly across the NAS. Some facilities use large and long-lasting restrictions to transfer delay away from a capacity-bound airport, whereas other facilities use very short and dynamic restrictions to smooth flows in a metering-like fashion. In some situations, actual flows are adjusted so that they are in line with the restriction. In other situations, restrictions may be in place, but actual flows are not curtailed and far exceed the restriction.

During the next year, CAASD will continue to work with the ATCSCC to further reduce the unnecessary use of restrictions in the NAS. The need for special case studies will remain; however, there is also an increasing need to provide simpler, more real-time metrics by which restrictions can be evaluated.

ELIMINATING ATC PREFERRED ROUTES

The FAA has recently eliminated 170 ATC preferred (also call "pref") routes. There are more than 2,000 pref routes listed in the *Airport/Facility Directory* (*11*). These routes often diminish the capacity of today's airspace and require flights to burn more fuel than necessary. In calendar year 1998, the FAA eliminated an initial set of 70 high-altitude pref routes: 50 serving specific U.S. airports and 20 special high-altitude route segments into a select few airports. Results of this effort are described elsewhere (*12*), and the 50 airport-airport routes eliminated in calendar year 1998 are shown in Figure 2.

In June 1999, the FAA eliminated an additional 100 high-altitude routes: 81 of these serve specific U.S. airports, and 19 are route segments into the Portland, Oregon; Seattle, Washington; and Vancouver, British Columbia, terminal areas. The 81 airport-to-airport routes eliminated in calendar year 1999 are shown in Figure 3.

CAASD has assisted the ATCSCC by providing an operational assessment of eliminating pref routes. Metrics analyzed include route usage, ATC sector counts, flying times, and analysis of graphical plots of traffic patterns. CAASD found little effect from eliminating the 170 routes. This was due to the fact that (*a*) most airport-to-airport routes eliminated had little traffic and (*b*) users were already shortcutting or deviating from the routes to save time and fuel. Only a few routes had a significant amount of traffic before they were eliminated, but no major shift in traffic was detected after the routes were placed on test elimination. No evidence was found that any ATC sectors in the United States have experienced sector-count increases over the MAP due to eliminating a pref route.

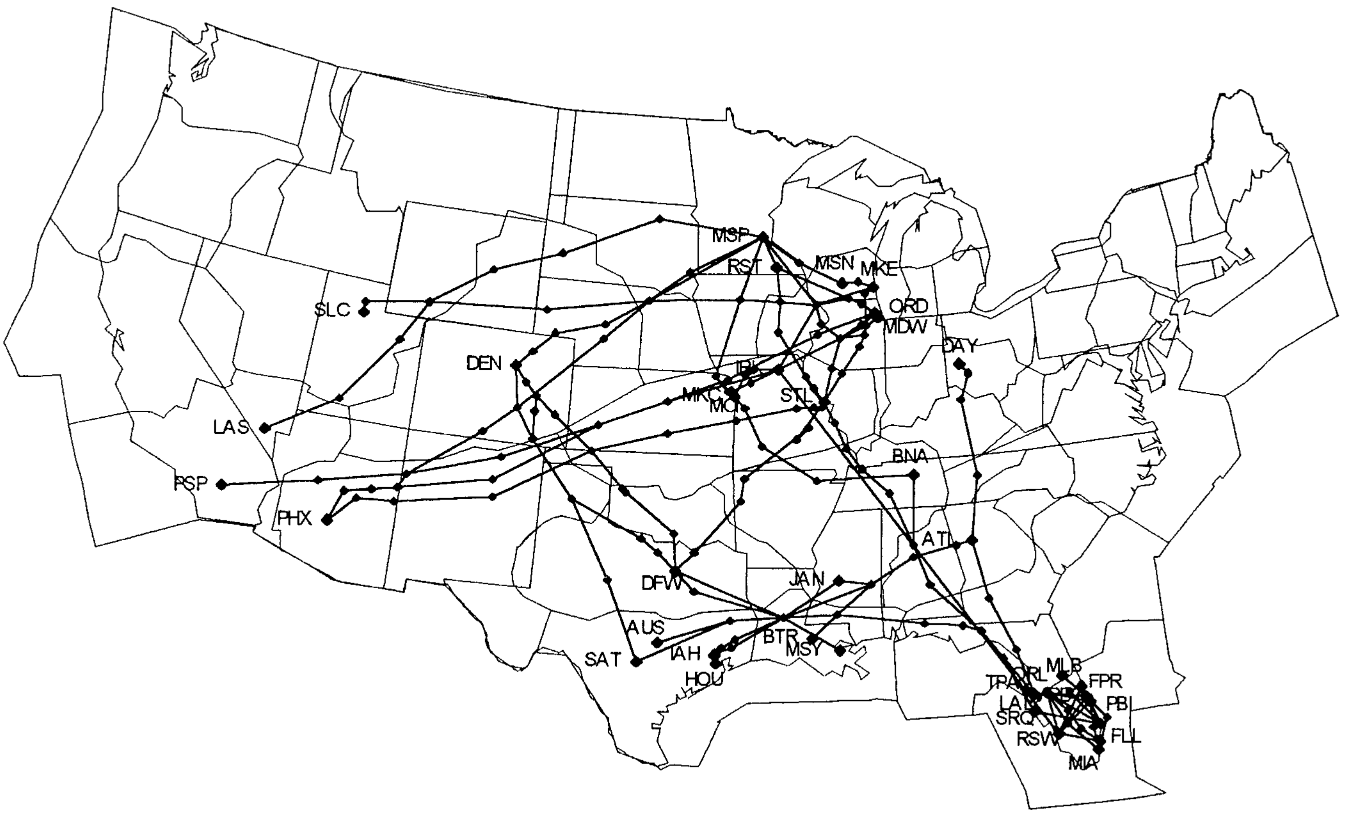

FIGURE 2 ATC-preferred routes eliminated in calendar year 1998.

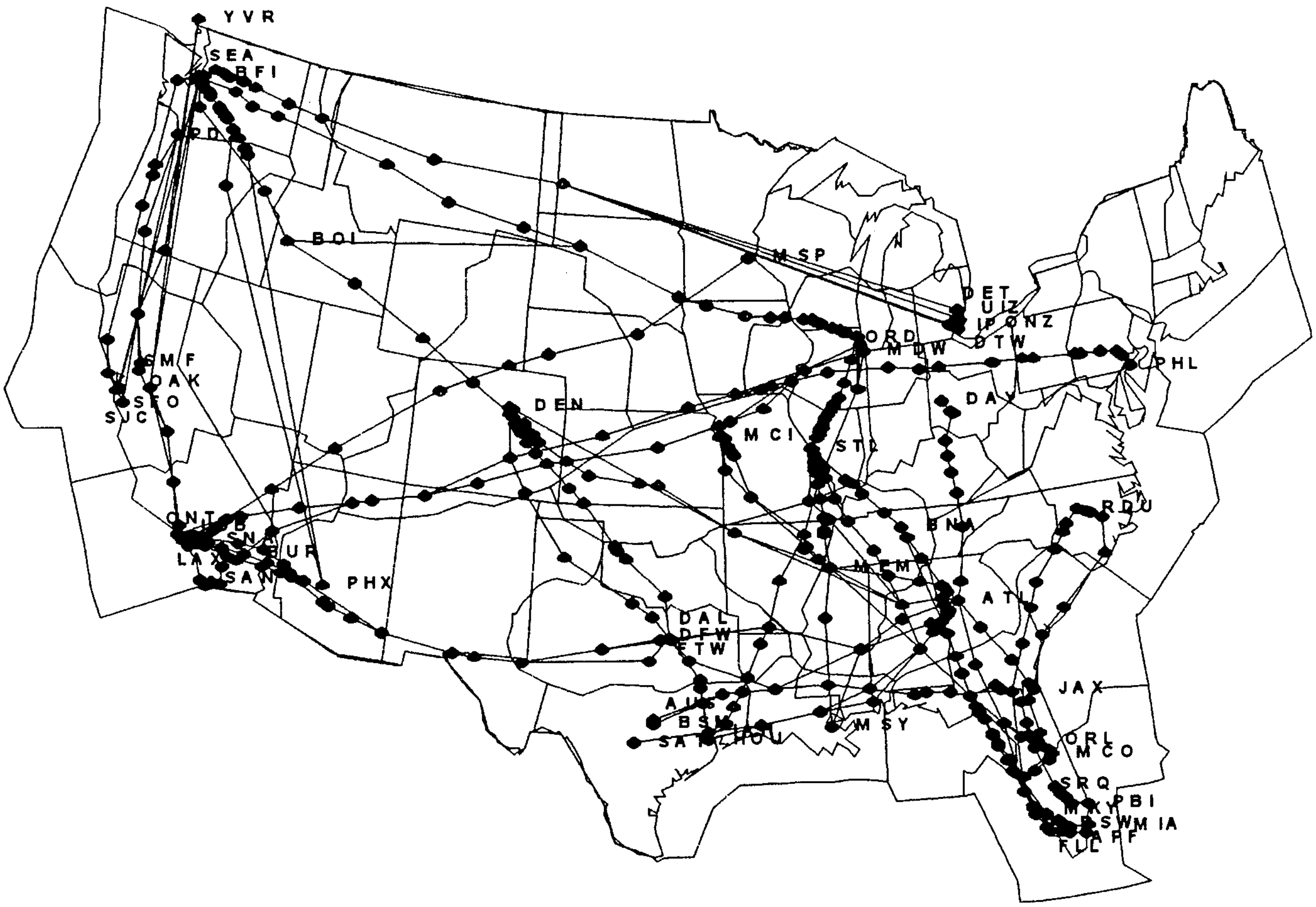

FIGURE 3 ATC-preferred routes eliminated in calendar year 1999.

The economic benefits to users from eliminating the 131 airport-airport routes are so far marginal, because little measurable flying time saving has yet been found that can be directly attributed to route elimination. From track data, CAASD has found a small flown distance saving (1 to 5 mi) for a few flights after eliminating two of the special high-altitude route segments into Portland.

CAASD has confirmed that eliminating pref routes reduces pilot-controller communications by necessitating fewer reroutes after takeoff. Before the second set of 100 routes was eliminated, 44 percent of flights filed one of the 81 airport-to-airport pref routes. After these routes were eliminated, that percentage was 37 percent. Before the routes were eliminated, the percentage of flight tracks approximating one of these routes was 17 percent. After the routes were eliminated, the percentage was 11 percent. Thus, many more flights actually file a pref route before takeoff than fly close to it from takeoff to landing. When traffic and weather conditions permit, ATC is clearing many pilots after takeoff direct to a point farther down the route. By eliminating pref routes, users have more freedom to file different, more direct routes. Thus, pilot-controller communications are being reduced due to fewer reroutes after takeoff.

CAASD has also examined an additional 160 high-altitude pref routes. These include a top-down look at the high-altitude pref routes serving the 50 airport pairs in the United States having the heaviest connecting traffic, as well as 133 high-altitude pref routes whose potential elimination was questioned by one of the involved ATC en route centers. The FAA successfully eliminated four routes in the top-down set in calendar year 1999. The statistics again show that many pref routes serve little or no traffic. They also show that, for many routes that serve pairs of airports with significant connecting traffic, either most flights do not file the route or most flights divert from the route after takeoff in order to fly more direct. This analysis will be used in subsequent consideration of route elimination candidates.

While examining the effects of eliminating routes, CAASD investigated the ability of several metrics to predict flight patterns after a pref route is eliminated. The most useful metrics were found to be the following.

- Pref route distance.
- Pref route relative inefficiency. The relative inefficiency of a pref route is defined as the pref route distance minus the Great Circle Route (or direct) distance, divided by the Great Circle Route distance. If the pref route is direct from airport A to airport B, then its relative inefficiency is zero. The average relative inefficiency of all the high-altitude pref routes in the NAS is 0.04. A few pref routes have a relative inefficiency above 0.3.
- Number of aircraft that fly the pref route. For present purposes, a flight is said to fly a pref route if its track averages within 6 nautical mi lateral distance of the route during the effective hours of the route, and given that the flight's filed altitude is consistent with the pref route's being either a high- or low-altitude route.

- Number of aircraft that do not fly the pref route but could. This is the number of aircraft that fly from airport A to airport B at an appropriate filed altitude but do not fly the pref route.

Based on analyses of traffic and the above metrics, in late 1999 CAASD recommended to the FAA the following strategy for eliminating future ATC preferred routes. The strategy is based on the principle of maximizing the number of deleted routes and minimizing, if not eliminating, negative impacts.

- First, routes with little or no filed traffic should be eliminated. These routes serve either airport pairs no longer having any significant traffic or airport pairs with significant traffic but where users no longer are filing the route.
- Second, very efficient or almost direct routes having a relative inefficiency of 0.01 or less should be eliminated. Most often these are short routes, but occasionally they are more than 500 nautical mi. They offer little or no benefit over flying direct.
- Third, pref routes where most flights shortcut or divert from the route after takeoff are good candidates for elimination or restructuring. These include inefficient routes with significant shortcutting as well as longer routes serving cities with NRP traffic. Longer pref routes tend to have little traffic unless they are wind-optimal. Ninety-four percent of the airport-to-airport pref routes eliminated in fiscal year 1999 fall into one of the above three categories. This indicates that eliminating these types of routes often has no negative ATC or airspace user impacts.
- Fourth, inefficient (relative inefficiency > 0.05) pref routes not in congested airspace but with a significant amount of traffic filing and closely approximating the route should be considered for elimination. Eliminating these routes may significantly benefit users without negatively affecting surrounding traffic. Only 3 percent of routes eliminated in 1999 fall into this category, and only 3 percent of the routes eliminated fall near this category with a relative inefficiency between 0.01 and 0.05.

Eliminating or modifying any further routes beyond these four categories may be difficult without interfering with other traffic patterns in nearby congested airspace, as in the Northeast corridor. Because of this and the presence of airspace redesign teams at many ATC centers, further elimination of pref routes, apart from such redesign efforts, has reached an incremental stage. In parallel with this, however, is the fact that the FAA is instituting new, more fuel-efficient pref routes. These new routes are a direct result of FAA discussions with airlines that do not wish to wait for inefficient routes to be eliminated.

CONCLUSION

Near-term procedural enhancements are being implemented to help improve the NAS today. The analysis and implementation of four of these enhancements, each of which has yielded incremental efficiency benefits to the NAS, have been reviewed. Although the specific benefits of some of these enhancements are relatively small, they are positive and quite real. Study of these enhancements also has shown how well the NAS is currently operating, because only small improvements can be realized in the near term. As these and other procedural enhancements (5) are implemented, NAS users will continue to benefit from gradual improvements until FFP1 and longer-term automation improvements become available. CAASD will continue to help design, analyze, and implement those enhancements that provide the most benefit to the NAS.

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Estimating Capacity of Europe's Airspace Using a Simulation Model of Air Traffic Controller Workload

Arnab Majumdar and John Polak

The growth in European air traffic has led to delays, inefficiencies, and attendant costs. This growth is predicted to increase. The workload of the air traffic controller is the limiting factor in airspace capacity and will remain so despite the introduction of new technology and procedures. A framework is provided for modeling airspace capacity by considering the factors that affect controller workload and then using a model of controller workload, aided by the appropriate analytical techniques, to estimate airspace capacity. The context of the current European air traffic control problems is given, airspace capacity is examined, and a scheme is outlined for estimating airspace capacity using simulation modeling. The Reorganized ATC Mathematical Simulator (RAMS) controller workload model was chosen for use in the research. The output of this simulation model is used for estimating airspace capacity, and simulation experiments undertaken using RAMS are described. The analysis of how these factors affect the air traffic controller, using a generalized linear modeling framework, is undertaken. This accounts for the spatial correlation structure of the error structure. Two alternative estimation methods are used: maximum likelihood and estimated generalized least squares. The results from the analysis, together with a workload-based capacity measure, are used to provide airspace capacity estimates.

Air traffic controllers play a vital role in ensuring that all aircraft under their jurisdiction maintain safe separation in the airspace through which they pass. This airspace is divided into air traffic control (ATC) sectors, which are geographic volumes of airspace. Controllers are assisted by technology and international regulations. The role of controllers is becoming more critical as air traffic growth in Europe rapidly increases. For example, in the period between 1985 and 1990, air traffic in Europe increased by 7.1 percent annually (*1*). Furthermore, this air traffic is unevenly distributed throughout Europe, with the existence of a "core area," consisting essentially of the London-Brussels-Frankfurt-Milan (including Paris) area, where air traffic density is greatest. Forecasts indicate a growth in air traffic for Europe between 1990 and 2010 of 110 percent, leading to more than 11 million flights per year over Western Europe in 2010 (*2*). Demand in the core area is forecast to increase by 2010. Hence, already-very-busy controllers in this core area will have to control more aircraft in the future.

The major problem is the lack of a single, integrated ATC system throughout Europe. Each nation controls and manages its ATC infrastructure and air traffic within its airspace, leading to technology incompatibilities and duplication of tasks and information. Among the major implications of these two factors are

- A rise in flight delays in Europe,
- Nonoptimal flight profiles,
- Extra route lengths, and
- Possible safety issues.

The economic impact of delays, as well as other inefficiencies in the ATC system (e.g., nonoptimal flight profiles), was calculated in 1989 to cost Europe $5 billion (in 1988 U.S. dollars) (*3*). The European Commission also confirmed this figure in December 1999 (*4*).

In the late 1980s, the European Organization for the Safety of Air Navigation (EUROCONTROL) developed the European Air Traffic Control Harmonization and Integration Program (EATCHIP) (*1*) to tackle the airspace capacity problems (*5*). EATCHIP aims to progressively harmonize and integrate the diverse ATC systems throughout Europe. To do this, it will use new technology, both in the control room and in the air [e.g., mandatory area navigation (RNAV) equipment on aircraft to enable greater position precision than at present] and innovative control procedures (e.g., flexible use of airspace between civil and military ATC).

EATCHIP has achieved many of its objectives, and it has had some success in reducing the capacity problem. For example, capacity has increased 40 percent since 1990 to cope with a 35 percent increase in air traffic during the same period (*6*). However, the delays have not disappeared.

With predicted air traffic growth, EATCHIP has been replaced by the European Air Traffic Management Program (EATMP) (*7*), whose main characteristic is the "gate-to-gate" concept, which treats flights as a continuum from the first interaction with ATM until post-flight activities. To do this, a broad range of measures and technology is considered that has the potential to change the way in which controllers will work in the future ATC system of Europe.

The success of any initiatives to improve current airspace capacity, as well as to improve capacity in the future, depends on a reliable definition and measure of airspace capacity. Herein lies a major hurdle, because airspace capacity in Europe is a concept with the potential to cause considerable difficulties, being dependent not only on spatial separation criteria but also on the workload of air traffic controllers.

This paper aims to provide a method of determining Europe's airspace capacity using a simulation model of air traffic controllers' workload and to the best of the authors' knowledge is the first such rigorous analysis of this problem. The paper covers the difficulties in measuring and understanding airspace capacity, outlines a method of estimating airspace capacity using a simulation model of controller workload, discusses controller workload models, and considers one model for further use—the Reorganized ATC Mathematical Simulator (RAMS) (*8*, *9*)—in a series of simulation experiments. An appro-

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priate model from these studies is proposed, and the results from ML analysis, with corrections made for spatial analysis, are reported. Finally, a "capacity curve" to estimate the capacity in an ATC sector is presented.

AIRSPACE CAPACITY

Unlike the situation in surface transport, airspace capacity is not defined simply by internationally specified spatial separation criteria between aircraft, based on their performance. The experience in high air-traffic-density areas such as Europe suggests that a safer measure of capacity is based on air traffic controller workload (i.e., the mental and physical work done by the controller to control traffic). Thus, airspace capacity is related to controller workload, given that the controller's workload limits determine the capacity of a sector.

With this in mind, the capacity of an ATC sector can be defined as the maximum number of aircraft that are controlled in a particular ATC sector in a specified period while still permitting an acceptable level of controller workload. Note that one is dealing with the number of aircraft controlled (i.e., aircraft whose control generates work for the controllers), rather than the number of aircraft entering, exiting, or passing through the sector, in a given period of time. Given this definition, the following need to be determined:

- What is meant by controller workload,
- How controller workload is measured, and
- The acceptable level of controller workload (i.e., the threshold value at capacity).

Controller workload is a confusing term with a multitude of definitions and models in the literature. Its measurement is not uniform (*10*). Workload is a construct (i.e., a process or experience that cannot be seen directly but must be inferred from what can be seen or measured). Research, theory, models, and definitions of workload are interrelated, and there are numerous reviews of workload and its measurement [e.g., Gawron et al. (*11*)]. Again, experience of airspace capacity in Europe and the United Kingdom suggests that the most appropriate measure for controller workload is based on the tasks, both physical and mental, and their timings that the controller must do to control air traffic (*12*). Such a measure can be thought of as a task-time measure of controller workload.

There are various methods of measuring air traffic controller workload, as noted by Hopkin (*13*). Controller workload assessments can generally be performed by

- Self-assessment of the controllers, either by instantaneous techniques [e.g., the subjective workload assessment technique (SWAT) (*14*)], or by noninstantaneous techniques [e.g., the National Aeronautics and Space Administration task load index (NASA-TLX) method (*15*)]; or
- Direct observation of the controllers by other controllers or by ATC system experts (e.g., detailed nonintrusive techniques).

Many of these measurement techniques can only be applied practically during real-time simulations (i.e., when controllers are controlling simulated air traffic in mock-up facilities). Only nonintrusive controller observations can be made operationally. In addition, a major problem with controller self-assessment techniques, or observer rating of workload, is the subjectivity bias of the controller workload measure.

The preferred solution for this study is to obtain a detailed, nonintrusive, objective record of the controller's actions. In order to properly account for the nonobservable cognitive tasks of a controller, such as planning, this record needs to be supported by controller verification of the tasks and their timings. By this method, it is possible to better account for the time controllers spend in the thinking and planning component of their tasks and thereby the "true execution time" for each task can be obtained (*16*).

Given that this workload measure includes only a measure of the physical and mental demands on the controller, it is more appropriate to deem the measure as the task load for the controller. For the purposes of continuity, the term "controller workload" will still be used to depict this task load.

The airspace capacity measure most frequently used in simulation modeling airspace studies in both the United Kingdom and Europe is that based on task-time definitions obtained from a detailed, nonintrusive, objective record of the controller's actions, aided by controller verification. Based on these task-time definitions, threshold controller loadings are defined for the numbers of minutes per hour controllers are occupied in their tasks as recorded by the models (*17*).

Irrespective of the definition and measure, research indicates that the workload experienced by air traffic controllers is affected by the complex interaction of (*18*)

- The situation in the airspace (i.e., features of both the air traffic and the sector);
- The state of the equipment (i.e., the design, reliability, and accuracy of equipment in the control room and in the aircraft); and
- The state of the controller (e.g., the controller's age, experience, and decision-making strategies).

These parameters can be thought of as the drivers of controller workload and consequently of airspace capacity (i.e., airspace capacity drivers). The effect of these parameters on airspace capacity must be understood if realistic and successful strategies for increasing capacity are to be implemented. Mogford et al. (*18*) provide a useful review of research, much of it qualitative in nature, on the effect of these parameters on controller workload. There also have been various recent attempts to quantify the link between controller workload and a number of these controller workload drivers. Such attempts fall into two categories:

- "Real-time" simulations (i.e., mock-up facilities) followed by controller questionnaires (e.g., the "dynamic density") concept of the National Aeronautics and Space Administration (*19, 20*) and research in the United Kingdom by the National Air Traffic Services (NATS) (personal communication, T. Lamoureux, 1999); and
- Analysis of historic data [e.g., by the FAA human factors group (*21*) on the separation loss between aircraft in the Atlanta airspace sectors].

These two approaches have provided significant insights on the parameters influencing controller workload and hence airspace capacity (see Table 1). However, both methods have problems their authors note. Another possible approach is the use of simulation modeling of airspace and controller workload to systematically vary a number of possible airspace and traffic parameters. Analysis of the output from the model can help formulate a functional relationship between the controller workload and the relevant parameters. Although various studies have been undertaken using simulation models of controller workload, by EUROCONTROL (*22*) and others, none has considered

TABLE 1 Air Traffic and Sector Factors That Can Affect ATC Complexity and Controller Workload

Air Traffic Factors	Sector Factors
Total number of aircraft	Sector size
Peak hourly count	Sector shape
Traffic mix	Boundary location
Climbing/ descending aircraft	Number of flight levels
Aircraft speeds	Number of facilities
Horizontal separation standards	Number of entry and exit points
Vertical separation standards	Airway configuration
Minimum distance between aircraft	Proportion of unidirectional routes
Aircraft flight direction	Number of facilities
Predicted closest conflict distance	Winds

the impact of varying such parameters on workload and then formulating a functional relationship. The following section describes this simulation modeling approach in more detail

SCHEME FOR AIRSPACE CAPACITY MODELING

Simulation Modeling Issues

Any simulation model chosen needs to model the conditions in European airspace as closely as possible with regard to the elements of the simulation (*12*):

- ATC sectors and their associated features (e.g., air routes);
- Air traffic (e.g., aircraft types and speeds); and
- Controller workload and procedures (e.g., conflict resolution rules).

One can carefully define the rules for the elements of the simulation in order to investigate their interaction and, on completion of the simulation, analyze the output from the model to derive functional relationships at an aggregate level. Magill (*23*) outlines the advantages of simulation modeling in ATC systems. However, Magill (*23*) does address an issue concerning the use of such a model, in that to make effective use of the simulation, "it is desirable to have a simple means to characterize the work done by the ATC system" (p. 2). This issue was dealt with when a task time–based workload measure of capacity was chosen for this research. In addition, two other concerns remain with a simulation modeling technique:

- How well the simulation model used represents the reality of the ATC system, and
- What rules for the elements of the simulation model need to be encompassed for the simulation scenarios in order to generate the appropriate output for analysis.

Bearing this in mind, it is possible to generate a perfectly adequate general capacity model, as outlined below.

Method to Estimate Airspace Capacity

A procedure used by the U.K. National Air Traffic Services (*24*) and EUROCONTROL for the RAMS controller workload simulation (*17*) can be used to estimate the capacity of an airspace system (Figure 1). This procedure can be summarized by the following steps:

1. Define the physical characteristics of the air traffic system. This is conceptually simple for the existing ATC network. The following characteristics would need to be defined: (*a*) the airspace sectors and their horizontal and vertical boundaries (geographic locations); (*b*) the number of flight levels in each sector; (*c*) the air routes through the sectors, composed of a series of navigation aids defined by geographic coordinates; and (*d*) the airport locations, in geographic coordinates. Although these are directly observable, data collection and analysis are time-consuming.
2. Once the airspace sectorization and routing have been designed, define the traffic demand through the sectors. This involves definition of the aircraft types and their associated performance characteristics (e.g., speed, climb, and descend rates), as well as their chosen routes. This also applies for any forecast traffic demand.
3. Define the rules for assessing the capacity of an individual ATC sector for use in the simulation model of air traffic controller workload. This requires a base of tasks and timings for the controller's work and the definition of controller workload threshold for capacity based on these tasks. Also, by the choice of geographic area simulations, it is possible to examine how a network of airspace sectors interlocks to assess the capacity of a geographic region of airspace.
4. From the output of the runs of the simulation model, undertake statistical analysis to derive a functional relationship between airspace capacity and the airspace capacity drivers, mentioned previously.

The rationale behind Step 3 is that in Western European en-route airspace sectors, with the current level of technology, the limiting factor on airspace capacity is air traffic controller workload, both for observable, physical tasks and for nonobservable, mental tasks. Long-term technology advances may so affect the ATC environment (e.g., the greater accuracy and precision of navigation equipment), that the controller's current tasks and workload may be replaced by spatial-temporal criteria in determining airspace capacity. In the short to medium term (the next 25 years), however, the controller remains the vital element in ensuring the safe movement of air traffic. Even with the technology enhancements proposed for future ATC systems, controllers will remain an essential part of the ATC scenario, although their task bases will be very different.

As a priority, the simulation model chosen must realistically reflect the "real-world" airspace environment being simulated. Once this is done, then to use the workload estimates from a model-based simulation, the model needs to be sufficiently well calibrated to give reasonable assessments of workload. The defined acceptable level is suitable for that calibration. Mention has been made of the various methods of measuring air traffic controller workload. The task-time thresholds mentioned for various air traffic controller workload simulation models have been validated by several real-time studies and the experience gained from previous simulation results, as well as from field studies (*12, 17, 25*).

CONTROLLER WORKLOAD MODELS

There are two main types of air traffic controller workload models: analytic and simulation. Analytic models are relatively straightforward equations, often simple regression equations, in which a predicted output can be rapidly generated from the mathematical analysis of a specified set of inputs.

Two examples of the analytic controller workload model are the Sector Design Analysis Tool (SDAT) devised in the United States (*26*) and the Capacity Indicators Model (CIM) used by

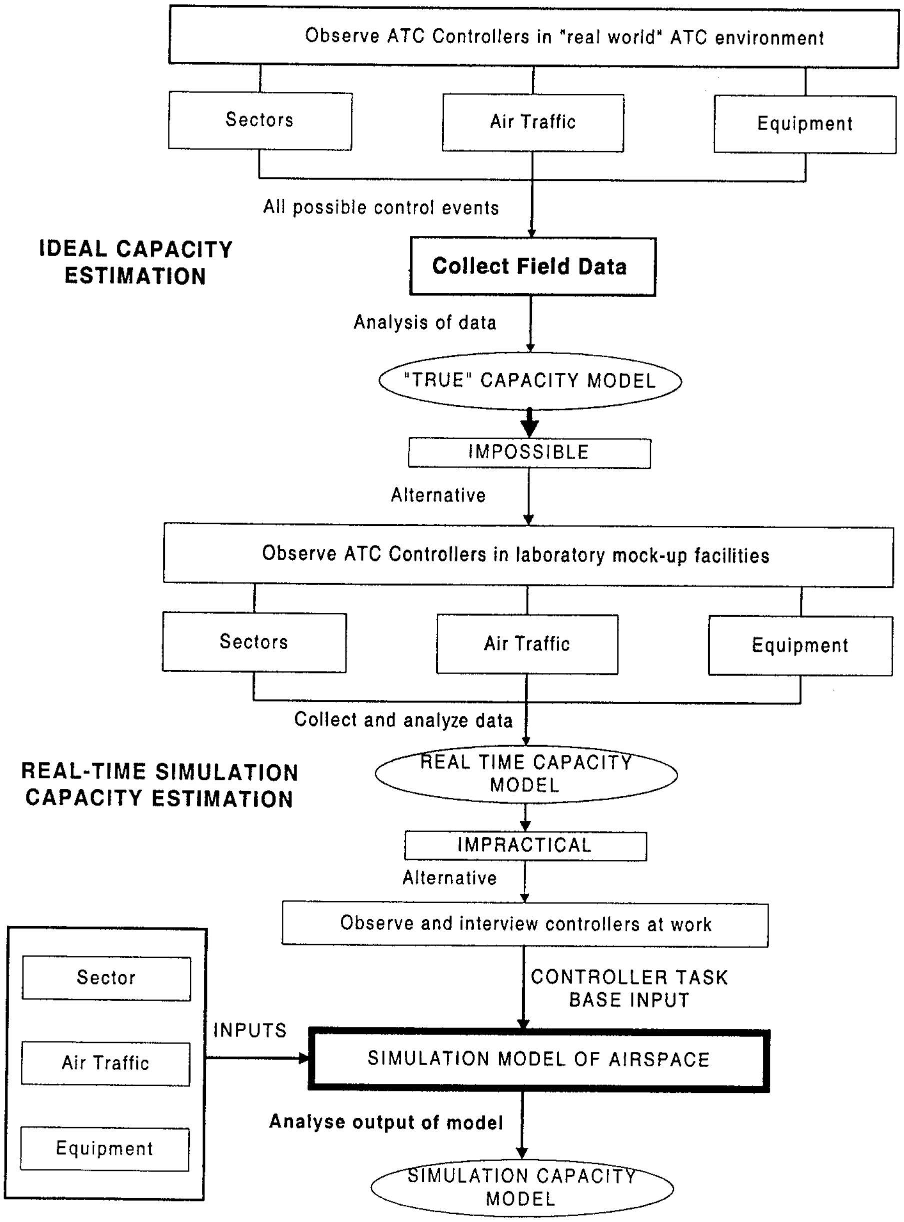

FIGURE 1 A method to estimate airspace capacity using a model of air traffic controller workload.

EUROCONTROL (*16*). Both determine the workload in a sector, given the associated sector tasks, and use probabilistic models to predict the expected number of conflicts in the sector and the resolution strategies to resolve them.

Simulation models are more complex. They are run given a number of operating rules specified in computer language. Inputs and changes (events) are delivered to the model over time, and then the computer generates a set of performance outputs, typically probabilistic ones. Simulation models are often necessary in systems such as ATC for two major reasons (*27*):

- The great complexity of the system prevents its behavior from being captured by analytic equations, and
- The inherently dynamic behavior of the airspace is well suited for a dynamic simulation.

There are two major simulation controller workload models: DORATASK (*12*), developed and used specifically for the U.K.'s ATC sectors, where its results have been validated; and the Reorganized ATC Mathematical Simulator (RAMS) (*28*). Also, NATS is now developing a model of air traffic controller workload based on the cognitive tasks of a controller. It is known as the Performance and Usability Modeling in ATM (PUMA) model (*29*).

REORGANIZED ATC MATHEMATICAL SIMULATOR (RAMS)

The RAMS model, chosen for this particular analysis, is a discrete-event simulation model that has been used widely for 25 years in Europe for airspace planning and has been verified by controller use

(*17*). In the RAMS model, each control area is associated to a sector, which is a three-dimensional volume of airspace as defined in the real situation. Each sector has two control elements associated with it, a RAMS planning control and a RAMS tactical control, shown in Figure 2. These areas maintain information about the flights wishing to penetrate them and have associated separation minima and conflict resolution rules that need to be applied for each of the two RAMS control elements. This reflects the teamwork aspect of control seen in practice. The simulation engine permits the input of rules for the controllers that mimic reality. The tasks for the controllers in RAMS are based on a total of 109 tasks undertaken by controllers, together with their timings and position, grouped into five major areas. These tasks are derived from a number of reference sectors in Europe, which include sectors in the London region, Benelux countries, France, and Germany. Furthermore, a cloning engine enables the current air traffic to be cloned to produce future traffic demands. The use of RAMS for this study means that the following definitions are used (*17*):

- Controller workload is a task-time measure, and
- A control team (tactical and planning) is at capacity at 42 min/h.

A range of methodological issues with the use of such a simulation model needs to be addressed. In particular, the simulation must replicate the "real-world" situation as closely as possible. Figure 3 shows the major inputs and outputs of the RAMS model. The application of appropriate "rules" for the inputs of RAMS deals with the following issues of the simulation:

- Area of airspace simulated—the characteristics of the ATC sectors and the air routes through them are contained in the sector data input files;
- Air traffic simulated—the characteristics of the aircraft and their performance capabilities are contained in the air traffic data input files; and
- The simulated controller tasks—the set of controller's tasks and their timings are contained in the controller task input files. The choice of an appropriate set and its implications are of the utmost importance in both undertaking and understanding the simulation results.

Note that in the current research, only the air traffic data are systematically varied in a series of simulation experiments, as shown by the shaded box in Figure 3. Neither the ATC sectors nor the controller tasks data are varied. In addition, in using RAMS the following practical considerations need to be taken into account: (*a*) the number of simulation runs and (*b*) computational and run-time constraints involved in the simulation exercise.

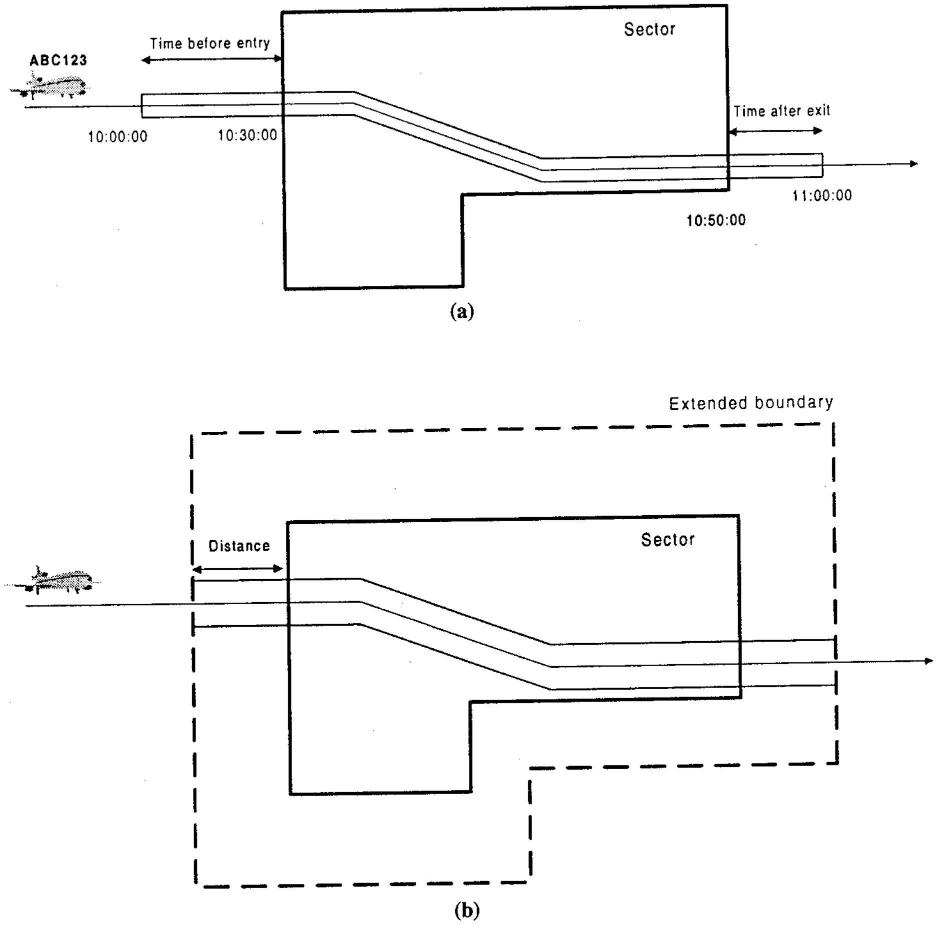

FIGURE 2 Control elements in RAMS: (*a*) planning controller conflict search range; (*b*) tactical controller conflict search range.

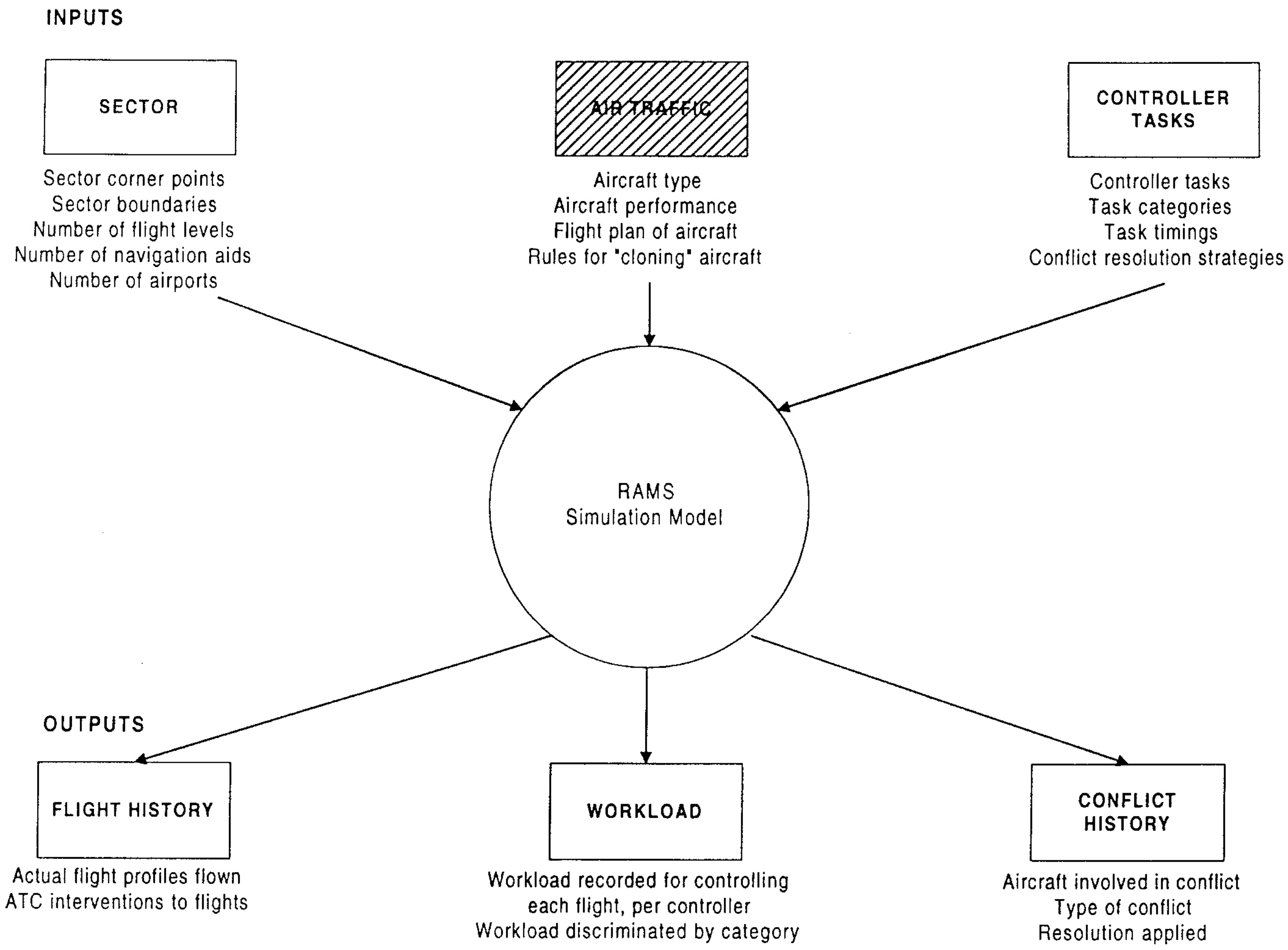

FIGURE 3 Inputs and outputs for the RAMS model.

The following section considers the experiments carried out using RAMS.

EXPERIMENTATION AND CHOICE OF INPUT VARIABLES

Simulation experiments were conducted on RAMS to test the effects of certain variables on the workload obtained from it. The salient points of the simulations are outlined below.

Airspace and Traffic Demand

The simulation area covered the 122 en-route sectors of continental Europe, excluding the United Kingdom. Figure 4 shows the geographic location of the sectors, and Figure 5 shows the distribution of navigation aids (navaids) throughout Europe, an indicator of the route density. The geographic data for the airspace were obtained from the EUROCONTROL database. Four traffic patterns were modeled:

- The current (1996) traffic for all 122 sectors,
- 25 percent increase in the current traffic for 67 ATC sectors in France and Germany,
- 50 percent increase in the current traffic for 64 sectors (except France and Germany), and
- 100 percent increase in the current traffic for 22 sectors with spare workload capacity.

The logic behind this is as follows. Computational constraints meant that Europe was subdivided into geographic airspace regions for the simulations (e.g., Germany and France). The number of sectors in such areas varied from 48 in French airspace to 2 in Danish airspace. When any sector in such a geographic airspace was assumed to reach workload at capacity (i.e., workload of the control team reached 70 percent of an hour), that airspace was assumed to be at capacity. After all, that particular sector is related to others adjacent to it, forming a bottleneck in the airspace. Ten replications per geographic scenario were run to account for randomness in the model.

The flight data consist of the scheduled flight data for a typically busy weekday in September 1996. Individual flights are defined by an entry time, entry cruise and exit flight levels (i.e., altitude), aircraft model, and a flight plan of navaids, airports, and runways (i.e., route). Flight profiles are dictated by the flight plan and aircraft performance. The flight path is four-dimensional, containing three-dimensional positions in space, each associated with time of arrival. The aircraft performance is dictated by each flight's aircraft model. The aircraft

FIGURE 4 ATC sectors of European airspace simulated in RAMS.

model is defined by the performance group (i.e., climb and descent speeds and rates) and aircraft group, which is used to specify wake turbulence separations.

Only the climb and descent rates to reach the requested flight levels are varied. The cruise, climb, and descent speeds represent ground speed and are not varied. As a consequence, overtaking conflicts between aircraft on the same route and same flight level were not modeled. However, other conflict resolution actions such as aircraft altitude change were used to compensate for overtaking conflict resolution.

The cloning engine cloned the current air traffic to allow future traffic scenarios to be explored under the assumption that the pattern of current air traffic demands and routes remains the same as at present.

The Controller

The choice of an appropriate controller task base is essential for confidence in the results. To this end, the task base for controllers of the

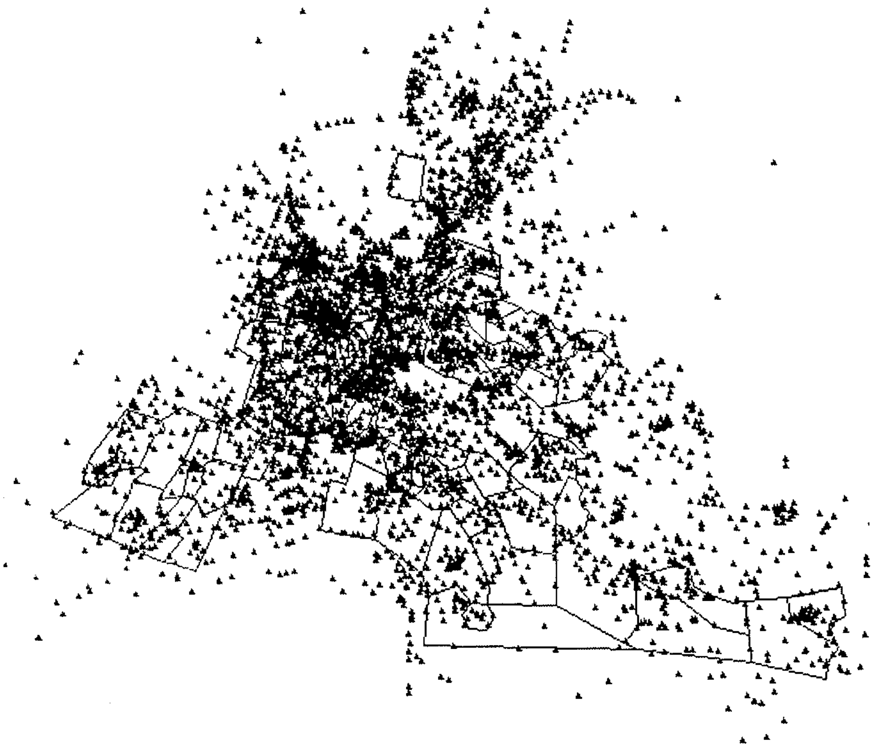

FIGURE 5 Distribution of navigation aids and airports in Europe as defined in the RAMS simulation.

Bordeaux (Southwest France) Area Air Traffic Control Center was used. The advantage of this task base was that it contained the timings given by the controllers for all their tasks, including those required in their strategies to resolve the various types of air traffic conflicts (i.e., the "true execution time"). This task base was divided into five categories:

- Internal and external coordination tasks,
- Flight data management tasks,
- Radio or telephone communications tasks,
- Conflict planning and resolution tasks, and
- Radar tasks.

This particular task set has been validated and used in sector planning (*22, 25*). As a consequence of choosing this task base, it is assumed that all sectors have the same equipment and level of technology as the Bordeaux sector, which is not necessarily the case (e.g., in sectors in Greece).

To model the control process realistically, entry distributions are attributed to each controller that specify a time offset before the sector pierce in which the flight is received into the controller's list. The distributions provide stochastic randomness to the time at which controllers begin controlling the aircraft, an uncertainty mirrored in the actual ATC process. Although international regulations allow for a separation of 5 nautical mi for en-route air traffic in areas of radar coverage, in practice this does not occur in controlled European airspace. Given the precision of ATC position equipment, the dynamic nature of ATC, and the difficulty in maintaining constant distance separation between aircraft of varying speeds, common practice is for controllers to maintain a time-based separation (e.g., 2 or 3 min between aircraft). This is modeled by a greater longitudinal and lateral separation between aircraft of 10 nautical mi and is further increased by the use of dynamic separation multipliers.

These dynamic separation multipliers increase the separation between aircraft based on the relative positions between the two flights. These multipliers rely on the dynamic situation of the flights during the simulation and not on the static values defined by airspace and aircraft type. They provide increased realism into the conflict detection, and the values chosen for the simulations reflect the much greater separation that must be required, for example, when aircraft are approaching each other than when aircraft are parallel to each other. ATC personnel involved in the RAMS simulation for the Bordeaux region provided the values for use in the simulations.

ANALYSIS OF RESULTS

The strategy used to attempt to formulate a functional relationship between controller workload and appropriate air traffic and sector variables is outlined in Figure 6. Table 2 lists possible regressors, divided into sector design and traffic structure, obtained from the RAMS simulation model. These regressors are similar to the factors listed in Table 1. The output data from RAMS of interest in this analysis are those for workload and flight history (Figure 3). Thus, for each traffic demand pattern, an attempt is made to fit an analytical model to the RAMS output data to determine the link between workload and the various flight and sector data.

Consider the analysis for the base or current air traffic simulation, covering 122 sectors. From forward selection and stepwise procedures for the selection of regressors, the only five variables significant to the 5 percent level of significance are

- Number of aircraft in cruise,
- Number of aircraft in ascend,
- Number of aircraft in descend,
- Total flight time, and
- Average flight time.

It is worthy of note that these significant variables are all traffic related, with no sector-related variable significant.

A variety of regression (ordinary least squares) models were fitted to these output data from RAMS for the current traffic simulation. The most appropriate model is shown in Table 3, which shows the results of a linear regression for a six-term model incorporating interactions between the various types of air traffic movement (i.e., ascend, cruise, and descend).

The presence of a positive intercept is essential, implying that even if there were no aircraft in a sector, controllers still would have work to do—communications, for example.

Heteroskedasticity

Table 3 also shows that the results of White's test, to determine the presence of heteroskedasticity (*31*), appear to indicate its presence. This means that the variances of the response variable, the workload in each ATC sector, are not the same. This is to be expected given that the current traffic simulation covers the whole of Europe's airspace, which presents a wide variety in the characteristics of the ATC sectors. One needs to make assumptions about the heteroskedasticity pattern, and from a variety of possible sources, the number of sectors that surround any given sector are chosen, as this can cause varying workload. If many sectors surround a particular sector, this may provide more entry and exit points in the sector and lead to a complicated traffic pattern within it. Should this be the case, the workload can be greater than if there are few sectors to provide entry and exit from the sector. However, it could be that the more sectors there are surrounding a sector, the less conflict there will be within the sector because many more alternative routes are provided for the air traffic. Table 3 also shows the results of a weighted regression (WLS). There does not appear to be much difference in the values between unweighted ordinary least squares (OLS) and the WLS with surrounding sectors, implying that the heteroskedastic effect in the data, although not negligible, is not very great.

Spatial Autocorrelation

Given the geographic nature of air traffic flow patterns, there is a likelihood of spatial autocorrelation in the data. Should such correlation exist, a correction needs to be made. A formal method of testing for spatial autocorrelation is by means of Moran's I_k test for the residuals obtained from an OLS or WLS analysis,

$$I_k = \frac{\hat{e}\mathbf{W}\hat{e}'}{\hat{e}\hat{e}'} \tag{1}$$

where $\hat{e}$ represents the error residuals from an OLS or a WLS. This equation requires the specification of a weights matrix, **W**, for the data. Consider here just the binary weights for the proximity **W** matrix (*32*), that is,

$w_{ij} = 1$, if ATC sectors i and j had a common boundary length,
$w_{ij} = 0$, if otherwise.

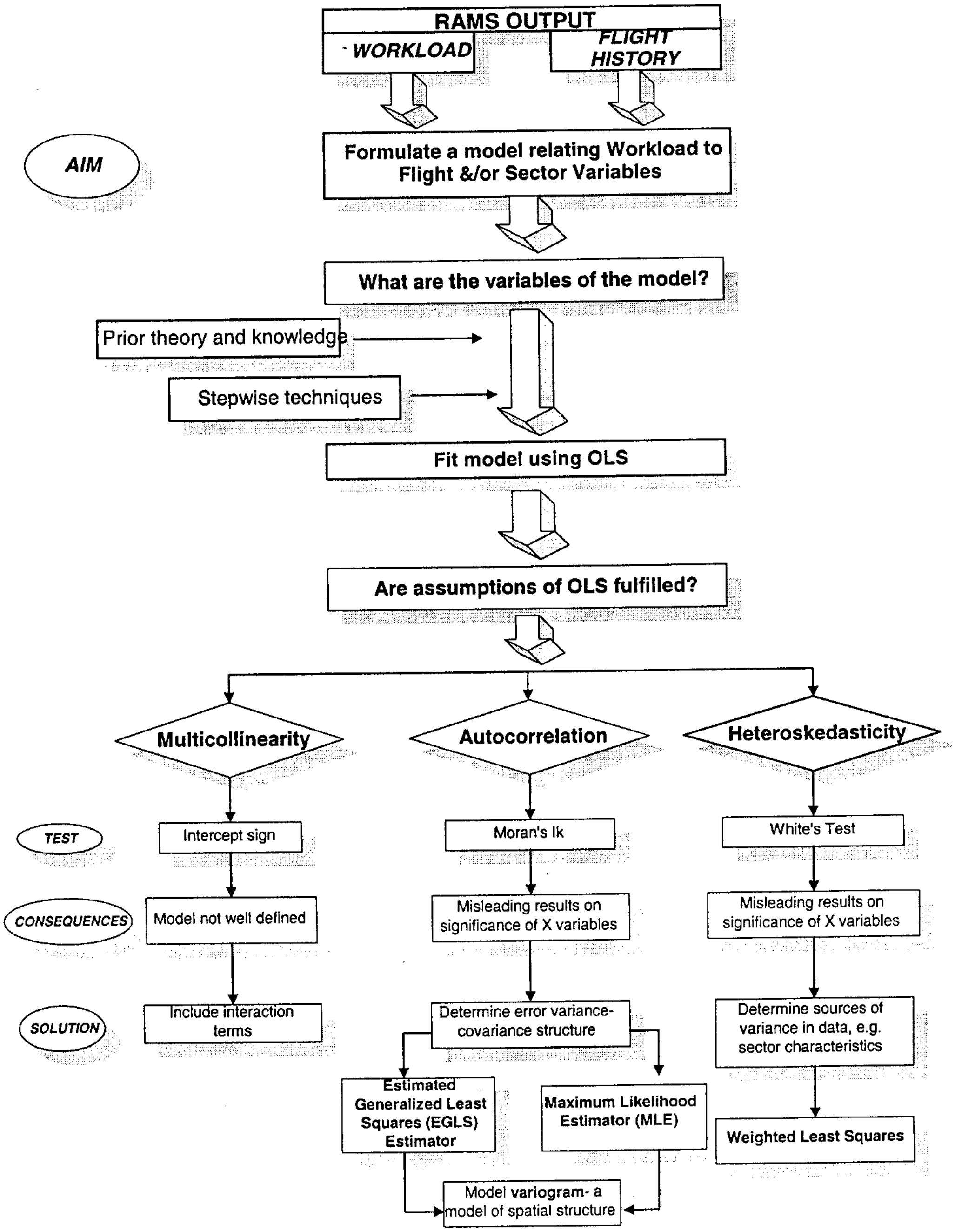

FIGURE 6 Modeling strategy.

TABLE 2 Possible Regressors

SECTOR DESIGN	TRAFFIC STRUCTURE
1. Volume of airspace	1. Total flight time
2. Number of airports	2. Average flight time
3. Number of navigation aids	3. Number of aircraft in cruise attitude
4. Number of intersection points	4. Number of aircraft in ascend attitude
5. Dimension of maximum side	5. Number of aircraft in descend attitude
6. Perimeter	
7. Number of vertical sectors	
8. Number of surrounding sectors	

TABLE 3 OLS and WLS (Surrounding Sectors) for the Current Air Traffic for Six-Variable Interaction Model (122 Sectors)

Weight	None		Surrounding	Sectors
Attitude Variable	$\hat{\beta}$	t	$\hat{\beta}$	t
Intercept	158.78	3.13	148.54	2.71
Cruise	55.48	9.15	56.95	9.11
Ascend	44.51	5.29	46.54	5.46
Cruise^2	-0.56	-8.84	-0.57	-8.26
Descend x Cruise	4.09	5.38	4.27	5.73
Ascend x Cruise	2.07	3.15	1.67	2.62
Descend x Ascend	4.86	5.26	4.98	5.26
Adjusted R^2	0.9282		0.9241	
Regression F	261.55		246.62	
White's Test, χ^2	21.708 Pr.=0.60			

Under the assumption of normality, the mean and variance of I_k are as follows:

$$E(I_k) = \frac{\text{trace}[(I - Px)\mathbf{W}]}{n - k} \tag{2}$$

$$\text{Var}(I_k) = \frac{\begin{matrix}\text{trace}[(I - Px)\mathbf{W}(I - Px)\mathbf{W}'] \\ + \text{ trace}\{[(I - Px)\mathbf{W}]^2\} + [\text{trace}(I - Px)\mathbf{W}]^2\end{matrix}}{(n - k)(n - k - 2)} - [E(I_k)]^2 \tag{3}$$

where $Px = X(X'X)^{-1}X'$ and k is the number of parameters in the regression model.

The standardized I_k statistic is asymptotically normal, so a one-sided test procedure for large samples to test for the presence of spatial correlation is as follows:

Test H_0: $\rho = 0$ (i.e., no spatial correlations) versus
H_a: $\rho \neq 0$ (spatial correlation)

$$\text{Reject } H_0 \text{ if} \quad z^* = \frac{I_k - E(I_k)}{\sqrt{\text{Var}(I_k)}} > z_{1-\alpha} \tag{4}$$

where ρ is a constant and is a measure of the overall level of spatial autocorrelation among the elements of the error term (e_i, e_k) for which $\mathbf{W}_{ik} > 0$. For example, $\mathbf{W}_{ik} = 1$ (unscaled) if i and k are physically continuous, and $\mathbf{W}_{ik} = 0$ if otherwise. If $\rho > 0$, then there is positive spatial autocorrelation among the residuals, whereas $\rho < 0$ implies negative spatial autocorrelation.

The results from the residuals obtained from the regressions carried out for the six variable models relating to the different attitudes of air traffic in a sector are given in Table 4. It can be seen here that a z-value of 1.86 corresponds to a one-sided probability of 3.07 percent, whereas a z-value of 1.62 corresponds to a one-sided probability of 5.26 percent. These results appear to suggest the marginal presence of spatial autocorrelation among the residuals at a 5 percent level. For the completeness of further analysis, the presence of spatial autocorrelation will be assumed.

METHODS TO ACCOUNT FOR SPATIAL AUTOCORRELATION

The presence of spatial correlation noted in the previous section requires correction. Consider the following regression equation:

$$y = X\beta + \epsilon \tag{5}$$

where

y = the response variable—workload in this case,
X = the matrix of regressor variables,
β = the unknown parameters, and
$\epsilon \sim \text{N}(0, \Sigma)$, the error or disturbance term.

TABLE 4 Results of Moran's I_k Test for the Six-Variable Model

	OLS	WLS (Surrounding Sectors)
Moran's I_K	0.458666	0.388073
$E(I_K)$	-0.06473	-0.06473
$var(I_K)$	0.078534	0.078534
Z*	1.867653	1.615752

In estimating the parameters β, the fact that the workload is spatially correlated is a nuisance factor whose influence should be accounted for in the analysis.

If one knows the variance-covariance matrix, then the best unbiased estimator for β is the generalized least-squares estimator:

$$\hat{\beta}_{GLS} = \left(X'\textstyle\sum^{-1} X\right)^{-1} X^{-1}\textstyle\sum^{-1} y \tag{6}$$

This estimator has the smallest variance of any linear estimator. However, almost always Σ is unknown. There are thus two ways to proceed. The first method is the estimated generalized least-squares process, in which one estimates Σ and then substitutes the estimate into the generalized least squares (GLS) expression. Thus, one has

$$\hat{\beta}_{EGLS} = (X'\hat{\textstyle\sum}^{-1} X)^{-1} X^{-1}\hat{\textstyle\sum}^{-1} y \tag{7}$$

Therefore, OLS can be used to obtain the residuals to estimate the covariance matrix Σ, and then the estimated generalized least-squares procedure can used (*32*).

However, when both β and Σ are unknown, as in this case, both can be estimated simultaneously using the method of maximum likelihood. This method involves the calculation of the joint likelihood of the observed response values (i.e., workload), given the values assigned to certain parameters. The likelihood function is given is Equation 8.

$$L(\phi \mid y) = f(y \mid \phi) \tag{8}$$

The aim is to find the value of ϕ most likely to have generated the observed data set.

Maximum likelihood estimators (MLEs) have the following desirable properties. They are

- Asymptotically normally distributed;
- Consistent (i.e., as sample size increases, the MLE tends toward the true value); and
- Asymptotically efficient (i.e., as sample size tends to infinity, the MLE has the smallest possible variance).

However, MLEs are not necessarily unbiased, and they require assumptions about the form of the distribution.

To obtain the form of the covariance elements of the variance-covariance matrix, there is a need to plot and estimate the variogram $\gamma_z(h)$ (i.e., model of spatial dependence or continuity) of the data. The formula for an empirical or experimental semivariogram $\gamma_z(h)$ is as follows. Denote the workload process by $\{Z(r_i), r \in D \subset \Re^2\}$, given workload measurements at positions $\{Z(r_i), i = 1, \ldots, n\}$. The standard formula for $\gamma_z(h)$ (isotropic case) (*33*) is

$$2\gamma_z(h) = \frac{1}{|N(h)|} \sum_{N(h)} [Z(r_i) - Z(r_j)]^2 \tag{9}$$

where $N(h) = \{i, j: |r_i - r_j| = h\}$ and $|N(h)|$ is the number of such pairs (i,j).

For actual data, it is unlikely that any pair (i,j) would exactly satisfy $|r_i - r_j| = h$, so typically a range of pairwise distances, $|r_i - r_j| \in (h - \delta h, h + \delta h)$, is used to group pairs (r_i, r_j) for a single term in the expression for $\gamma_z(h)$. Using this range modifies $N(h)$ by

$$N(h, \delta h) = i, j: |r_i - r_j| \in [h - \delta h, h + \delta h] \tag{10}$$

The covariogram (isotropic or direction invariant) for the ATC sectors of Europe is shown in Figure 7, for the current traffic scenario. It does not resemble any of the commonly known shapes. As Journel and Huijbregts (*34*) note, one is concerned with the behavior of the covariogram near the origin. It appears that there is a strong local or "nugget" effect, and near the origin at least (lag distance 1), the behavior is that of a "spherical" covariogram, whose formulation is given by

$$\gamma_z(h) = c_0\left[\frac{3}{2}\left(\frac{h}{a_0}\right) - \frac{1}{2}\left(\frac{h}{a_0}\right)^3\right] \qquad \text{for } h \le a_0 \tag{11a}$$

$$\gamma_z(h) = c_0 \qquad \text{for } h > a_0 \tag{11b}$$

where a_0 is the range and c_0 is the scale of the covariogram.

The shape of the covariogram leads one to suspect a nested structure—possibly a combination of the spherical and Gaussian covariograms.

Therefore Table 5 shows the results of ML estimation with the six-variable model, allowing for the spatial correction, as well as for heteroskedasticity, of the error term.

The following items should be noted from the ML analysis.

- It is asymptotically normally distributed.
- There is a sign change for variable $*\text{Cruise}^2$ compared with the OLS case (~ –0.5) to (~ 0.3 to 0.6). However this parameter is very small and could well be ignored.
- The $*\text{Cruise}^2$ variable is not significant at 95 percent confidence interval level.
- The intercept term is much higher than for OLS, around 70 s more.
- The cruise variable is considerably lower; the ascend variable is nearly the same.
- Heteroskedasticity in the data, although not negligible, is not large.

TABLE 5 MLEs for the Six-Variable Model with a Spherical Covariogram Structure

Weight	None			Surrounding Sectors		
Attitude Variable	$\hat{\beta}$	SE	t	$\hat{\beta}$	SE	T
Intercept	227.96	55.74	4.09	221.34	56.00	3.95
Cruise	35.97	7.89	4.56	39.36	8.12	4.85
Ascend	45.55	7.63	5.97	45.67	7.95	5.75
$*\text{Cruise}^2$	0.25	0.26	0.97	0.223	0.259	0.86
Descend x Cruise	3.43	0.70	4.87	3.74	0.717	5.22
Ascend x Cruise	1.88	0.59	3.17	1.599	0.595	2.67
Descend x Ascend	5.13	0.85	6.04	5.387	0.894	6.02
AIC (model fit measure)	-824.83			-831.23		

Given that Table 5 indicates that the Cruise^2 variable appears not to be significant, a ML analysis should be conducted with that variable removed. The parameter values for the resulting five-variable model are shown in Table 6.

CONCLUSIONS AND USE OF THE MODEL

With the parameters given by Table 6 for the current travel demand, a curve can be plotted of when the workload of the control team is assumed to be at capacity (i.e., 70 percent of an hour). (The choice of this threshold was explained earlier.) For example, in the case of the current traffic demand, one has the following equation:

$$\begin{aligned} \mathbf{W} = {} & 193.92 + 45.23(\text{Cruise}) + 46.2(\text{Ascend}) \\ & + 3.82[(\text{Descend})(\text{Cruise})] + 1.56[(\text{Ascend})(\text{Cruise})] \\ & + 5.34[(\text{Descend})(\text{Cruise})] \end{aligned} \tag{12}$$

At capacity, **W** is 42 min (2,520 s), and the combination of cruise, ascend, and descend aircraft that produces this workload needs to be determined. This "capacity curve" (Figure 8) indicates the theoretical

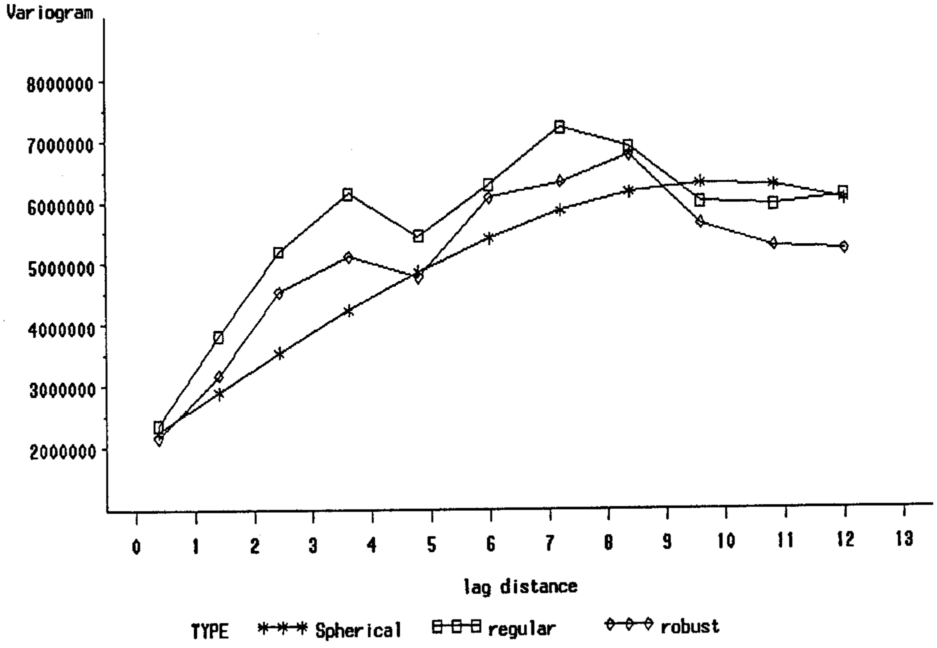

FIGURE 7 Covariogram of current traffic data for the ATC sectors of Europe compared with a theoretical spherical covariogram.

TABLE 6 MLEs for the Five-Variable Model with a Spherical Covariogram Structure

Attitude Variable	$\hat{\beta}$	t
Intercept	193.921	4.19
Cruise	45.225	10.17
Ascend	46.201	5.81
Descend x Cruise	3.820	5.35
Ascend x Cruise	1.560	2.61
Descend x Ascend	5.337	5.96
Log Likelihood	-828.602	
AIC	-831.602	

maximum number of aircraft in their various possible attitudes, based on Equation 12. Although one must reserve caution about the values at the origin of this curve [i.e., with 90 aircraft in descend when only 5 aircraft are in cruise (this could be due to the different nature of tasks that would be required at such low cruise and ascend traffic situations)], the resulting surface shows the traffic combinations that could be obtained when the control team is at capacity.

The value of such a curve is as follows. For a number of ATC sectors in European airspace, there exists a capacity measure known as the declared capacity, which is declared by the controllers of the sector as the maximum number of aircraft handled by them in the peak hour over a 6-month period. As an example of the use of these curves, consider the declared capacity value for four sectors in 1996. One of them, the EDDYLNO sector in the Maastricht area control center, had the highest declared capacity of any in Europe with 51 aircraft in the peak hour (source: Soenke Mahlich, head of Airspace Indicators Division), outlined in Table 7. The key for Table 7 follows.

- Column 1 gives the sector/airspace for which declared capacity figures are available. Due to the political sensitivities associated with sector capacity issues in Europe, the geographic locations of Sectors A, B, and C are not identified.

TABLE 7 Workload Values Calculated for Four Sectors from the 100ML Model

Sector	Declared Capacity	Declared Cruise Aircraft	Declared Ascend Aircraft	Declared Descend Aircraft	MODEL 100ML Workload, seconds
EDDYLNO	51	26.52	11.73	12.75	4510.35
A	41	22.14	7.79	11.07	3220.64
B	35	23.8	5.25	5.95	2415.42
C	32	22.72	6.4	2.88	2091.28

- Column 2 gives the declared capacity—the peak-hour traffic handled as declared by controllers in their sector—over a 6-month period in 1996.
- Column 3 gives the average number of declared cruising traffic handled in the peak hour from the controllers' declared capacity breakdown.
- Column 4 gives the average number of declared ascending aircraft handled in the peak hour from the controllers' declared capacity breakdown.
- Column 5 gives the average number of declared descending traffic handled in the peak hour from the controllers' declared capacity breakdown.
- Column 6 indicates the workload calculated for the sectors based on the functional model derived for the current traffic demand.

The information from Equation 12 and Table 7 can be used in one of two ways.

Sector Efficiency

Given that the maximum workload at capacity for the ATC team, using the 70 percent workload threshold, is 2,520 s, then the workload efficiency of the sector can be determined using Equation 13.

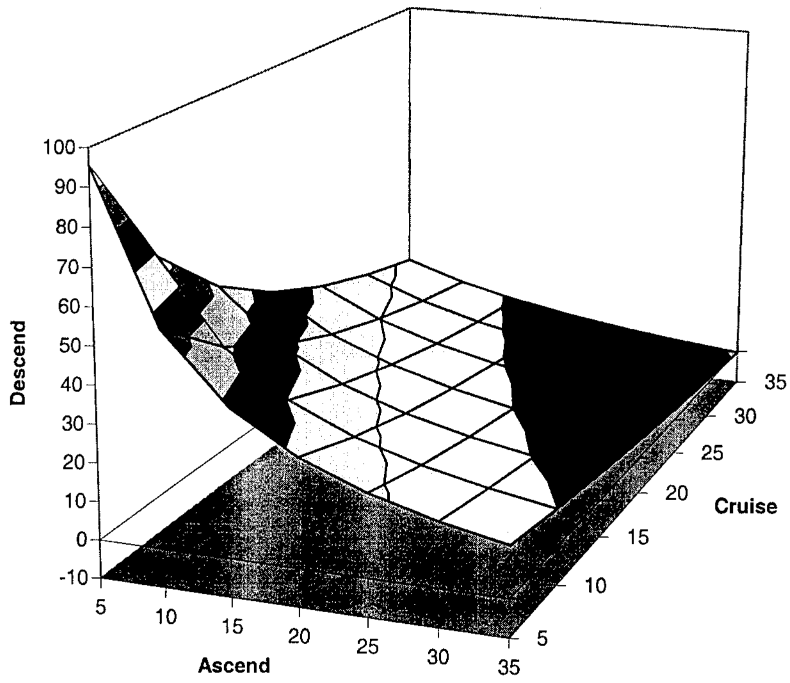

FIGURE 8 Capacity curve (70 percent of hour workload) for current traffic, five-term interactions model weighted by surrounding sectors (ML).

TABLE 8 Sector Efficiency (percentage) and Difference in Number of Aircraft for the Four Sectors Based on the 100ML Model

Sector	Declared Capacity	Efficiency of MODEL 100ML (%)	Declared Descend Aircraft	100ML Descend Aircraft	Difference Descend 100ML Declared
EDDYLNO	51	89.5	12.75	15.98	3.23
A	41	63.9	11.07	25.49	14.42
B	35	48.0	5.95	28.02	22.07
C	32	41.5	2.88	27.25	24.37

$$\text{Sector Efficiency} = \frac{\text{workload derived from functional } model\text{l}}{max\text{imum possible workload}} \qquad (13)$$

The results of using Equation 13 on sector efficiency are shown in Table 8.

Theoretical Number of Aircraft in the Sector

Alternatively, one can determine the capacity in terms of the number of aircraft theoretically possible using the equations derived earlier. For the current demand model, given the number of declared cruising and ascending aircraft, one can determine the theoretical maximum number of descending aircraft possible at the workload capacity of 2,520 s. This analysis is also shown in Table 8, the key for which follows.

- Column 1 gives the sector of airspace for which declared capacity figures are available.
- Column 2 gives the declared capacity of the sector/airspace.
- Column 3 gives the sector efficiency calculated using the current traffic demand model.
- Column 4 gives the declared number of aircraft in descent for the sector.
- Column 5 gives the calculated maximum number of aircraft in descent at capacity based on the parameters for the functional model of the current traffic demand.
- Column 6 gives the difference between the calculated number of aircraft in descent based on the current-traffic-demand functional model and the declared number of aircraft in descent for the sector.

These results of both the sector efficiency and theoretical number of aircraft possible appear to indicate that the sector EDDYLNO in the Maastricht airspace appears to be approaching the capacity that can be achieved using existing control technology and procedures. Sector B, too, appears to be at high sector efficiency. For the other sectors, there appears to be scope for an increase in the workload of descending traffic, so there appears to be spare capacity. However, remember that the declared capacity relates to air traffic conditions relevant to that particular sector. Unique traffic difficulties, demand conditions, and other factors could explain why certain sectors appear to have spare capacity. Alternatively, the assumptions behind the declared capacity figures need to be examined.

On the basis of an analysis similar to those in the preceding two sections for the other traffic demand patterns, Table 9 summarizes the relevant variables (indicated by $*$) relating controller workload to the air traffic movement variables for each demand pattern.

With four traffic demand patterns, each with its own functional relationship between the controller workload and the air traffic variables, a curve may be drawn for each demand pattern to indicate the traffic combinations that may be obtained when the control team is at capacity.

This paper has shown a method for estimating the capacity of Europe's airspace, given that this capacity is limited by the air traffic controller's workload. This method relies on a well-validated simulation model of the air traffic controller's workload, RAMS, together with the use of appropriate definitions of controller workload and threshold workload value at capacity. Based on a series of controlled experiments, the output from the RAMS model is used for a functional analysis to relate workload, and hence capacity, to its various possible drivers. Of interest in the functional analysis is the fact that simple classical OLS regression appears to be inadequate. Corrections have to be made for both heteroskedasticity and spatial autocorrelation in the data. Although the effects of both are not large individually, they are not negligible; combined, their effect does need to be accounted for. Having obtained a suitable functional model between the workload and the various air traffic movements, a "capacity curve" can be obtained to indicate the combinations of air traffic movements in a sector when the control team is at capacity. Such a curve can greatly aid planning by indicating any spare capacity in a sector, although the assumptions underlying the curve need to be noted.

TABLE 9 Summary of Relevant Variables for Each Demand Pattern

Demand	**Current**		+25%		+50%		+100%	
Variable	WLS	ML	WLS	ML	WLS	ML	WLS	ML
Cruise	*	*	*	*	*	*		
Ascend	*	*			*	*		*
Descend							*	*
Cruise^2	*							
Descend^2							*	*
Descend x Cruise	*	*			*	*		
Ascend x Cruise	*	*	*	*			*	*
Descend x Ascend	*	*	*	*	*	*		

There is a need for this model to be further refined. In particular, alternative task bases need to be used in this framework to determine whether the same variables as for the Bordeaux task base remain significant.

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Short-Term Delay Mitigation Strategies for San Francisco International Airport

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San Francisco International Airport (SFO) is typical of many large airports in that rapid growth in air travel has outpaced its available runway capacity, leading to serious delays. At the same time, SFO represents a unique circumstance because of the role of its local climate, and thus careful analysis is required to address its delay situation. The airport is in the process of planning a major runway reconfiguration project that would largely solve the problem of weather-related congestion delays, but this massive project will take many years. Presented are the results of an effort to design potential short-term strategies to reduce weather-related congestion delay at SFO while the runway reconfiguration proceeds. Designing measures to reduce delay outside the context of runway expansion is a complex task that requires balancing multiple considerations—issues of equity, access, legal jurisdiction—along with considerations of efficiency and airport performance. The kinds of thinking and analysis required in considering these types of delay-reduction measures are explored.

Constructed in the 1950s, San Francisco International Airport (SFO) has two pairs of parallel runways, intersecting each other at a right angle. This design was intended to allow two of the four runways to be used at all times (one for departures and one for landings), regardless of the wind conditions, and it was more than sufficient for the level of air traffic that existed at that time.

Since then, operations have more than doubled, so that the current level of demand can be served only by using all four runways simultaneously. But because each pair of runways is only 750 ft. apart, they cannot be used in this manner during periods of low visibility or when cloud ceilings are sufficiently low. The nature of San Francisco's local climate, a mix of the famous summer "fog" and winter rainstorms, makes this a chronic problem, with the airport suffering persistent and severe flight delays whenever these weather conditions occur.

SFO is planning a runway reconfiguration project that is designed to correct this problem by providing enough additional spacing between the runways to allow them to be used during most weather conditions, thus raising the bad-weather arrival capacity of the airport to near the good-weather level. Located south of the city on the peninsula, the airport is now hemmed in by the surrounding suburbs, and as a result airport officials have proposed filling several hundred acres of San Francisco Bay to accommodate the expansion. The environmental sensitivities of this proposal, combined with its estimated $2.5 billion cost, mean that it will take years to complete.

This paper presents the results of an effort to design potential short-term strategies to reduce weather-related congestion delay at SFO while the planning of the runway reconfiguration proceeds. The study was commissioned by the management of San Francisco International Airport and conducted by Charles River Associates (CRA) and the John F. Brown Company. (The authors are the three individuals at CRA who principally were involved in the study effort.)

Designing measures to reduce delay outside the context of runway expansion is a complex task that requires balancing multiple considerations—issues of equity, access, legal jurisdiction—along with considerations of efficiency and airport performance. Some of the thinking and analysis required in considering such delay-reduction measures are described, organized in three sections.

- Analysis of SFO's delay problem. This section summarizes the detailed analyses required to adequately understand the nature and extent of the airport's delay problem and the implications for the efficacy of potential mitigation measures.
- Context for policy analysis. This section discusses important issues common to all potential delay-reduction policies and identifies the key stakeholders potentially affected by any delay-reduction policy. The work done to analyze the interests and concerns of some of these stakeholders is described.
- Specific strategies examined. This section outlines the types of specific strategies examined and their estimated impacts.

Readers interested in understanding specific details of any of the analyses are referred to the detailed study report (*1*).

ANALYSIS OF SFO's DELAY PROBLEM

SFO has consistently been one of the most delay-plagued airports in the United States. For each of the last several years, it has been responsible for more delays than any other U.S. airport, and Figure 1 shows that on average it has caused almost twice as much delay as the next most delayed airport. ["Delay caused by the airport" refers to "estimated departure clearance time where-caused" delay as measured by the U.S. Department of Transportation's Consolidated Operations and Delay Analysis System (CODAS). CODAS measures delays against the airline schedule rather than an optimum engineering performance standard. This measure is appropriate for this analysis because most passengers are familiar with it.]

The analysis included an extensive examination of variations in delays during recent years, relating them to changes both in operations at the airport and in those weather patterns known to reduce the airport's runway capacity.

Identification of Weather Patterns

Although it was well known that SFO's delay problem derives from the interaction of its runway configuration and its local climate, a better understanding was needed of the nature of this climate as well

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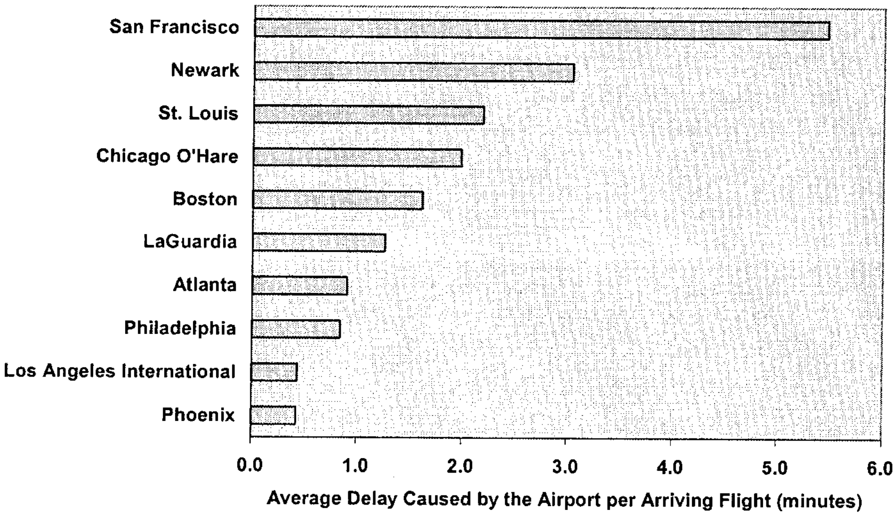


FIGURE 1 U.S. airports causing most delays, 1997–1999 (SOURCE: U.S. Department of Transportation, CODAS database).

as an assessment of its implications for the types of policies that might be most appropriate. By examining actual weather observations taken at the airport over the last several years, the weather could be classified into a few basic patterns. During winter storms, the weather in San Francisco typically remains bad all day, whereas the classic pattern of San Francisco's "fog" is to begin in the early morning but "burn off" by about midday. Table 1 shows that these were by far the dominant weather patterns and that more than 90 percent of delays at the airport occurred on one of these two basic day types.

Significant additional analysis of the weather data also was conducted to examine how these patterns change over time. Table 2 shows that there was substantial variation, particularly in the incidence of all-day bad-weather days, even over the past 4 years. Table 3 further illustrates that even for the classic foggy day, in which the weather is bad primarily in the morning, there is substantial variation in the time at which the fog typically "burns off."

The classification and detailed analysis of weather patterns in this fashion were essential to the development of potential mitigation strategies. The nature of operations at the airport is such that the effects of policies could differ significantly depending on the prevailing weather pattern. And the variability observed means that these weather patterns, and therefore the delays they cause, are highly unpredictable. This result obviously has very important implications for the effective implementation of any policy proposal.

Impact of Operational Changes

The total number of operations at the airport has not changed significantly in recent years, and seasonal variation in the total number of scheduled flights had consistently been within 5 percent of the annual average during the main summer and winter months. But significant changes in both the timing of flights and the type of aircraft used have occurred recently, as well as changes in FAA rules that effectively increased the minimum final approach separation requirements for a large number of aircraft using SFO.

Variations in the timing of flights throughout the day can have a significant impact on the magnitude of delays. Schedule "peaks," where many flights arrive at nearly the same time, can create large capacity shortfalls. And this is especially important in SFO's case,

TABLE 1 Distribution of Types of Bad Weather Days at SFO: 1997–1999

Day Type	Percent of All Days	Percent of Bad Weather Days	Percent of Bad Weather Hours	Percent of EDCT Where-caused Delay
Bad morning weather	29.5	59.0	36.0	39.5
Bad weather all day	14.6	29.3	55.8	55.4
Bad weather in aft./eve. only	2.7	5.5	4.8	2.4
All other	3.1	6.2	3.4	2.7
Total	50.0	100.0	100.0	100.0
Good weather all day	50.0	—	—	—

SOURCE: National Climatic Data Center, SFO tower logs, and CODAS data set.

TABLE 2 Number and Percent of Days During Which SFO Experienced Various Types of Weather: 1996–1999

Weather	1996		1997		1998		1999	
Good all day	197	54%	212	58%	152	42%	184	50%
Bad morning	87	24%	94	26%	113	31%	116	32%
Bad all day	63	17%	32	9%	75	21%	53	15%
Bad aft./even.only	8	2%	11	3%	13	4%	6	2%
Other	11	3%	16	4%	12	3%	6	2%
Total	366	100%	365	100%	365	100%	365	100%

SOURCE: National Climatic Data Center, SFO tower logs, and CODAS data set.

where so much bad weather occurs only in the morning hours when many flights are scheduled to arrive.

Figure 2 compares the total number of flights in each of the 1,080 15-min intervals between 6 a.m. and midnight—essentially a "rolling" 15-min total throughout the day—for 1994 and 1998. (There are 1,080 min between 6 a.m. and midnight—60 min × 18 hours). The graph represents the 15-min intervals beginning in each of these 1,080 min. Presentation of the data in this fashion strongly implies that the schedule has in fact become markedly less "peaked" since 1994. By modeling the impacts with SIMMOD, an industry standard airport simulation tool, it was possible to confirm that in fact delays would likely have been higher without the schedule changes. This implies both that there may have been some equilibration of the airline schedules in response to delays and that perhaps further equilibration might produce delay reductions. Practically speaking, however, this reasoning is subject to two very important practical limitations.

First, as more "peaks" are smoothed out of the schedule, there are likewise fewer and fewer "troughs" that can serve as recovery periods after delay-causing weather events. This can be seen clearly in the figure. Thus this kind of schedule equilibration is naturally subject to diminishing returns with respect to its delay-reduction benefits.

Second, the nature of operations at SFO does not allow much flexibility in shifting of arrival times. The figure shows that there are two main arrival peaks—one in the morning and one in the evening. These arrival peaking patterns are generally the result of two factors.

TABLE 3 Hour During Which Bad Weather Cleared on Morning Bad Weather Days During 1996–1999

Hour During Which Weather Cleared	Total Days	Percent of Total Days	Cumulative Percent
6:00	0	0.0	0.0
7:00	0	0.0	0.0
8:00	45	11.0	11.0
9:00	72	17.6	28.5
10:00	87	21.2	49.8
11:00	83	20.2	70.0
12:00	62	15.1	85.1
13:00	21	5.1	90.2
14:00	12	2.9	93.2
15:00	11	2.7	95.9
16:00	9	2.2	98.0
17:00	8	2.0	100.0

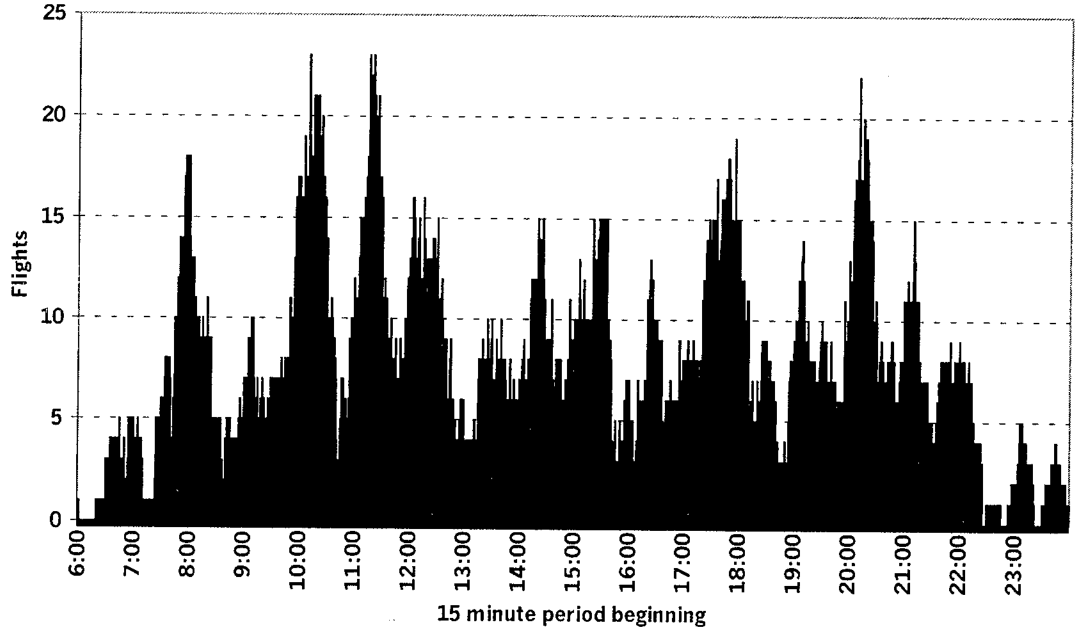
SOURCE: Analysis of data from SFO tower logs and National Climatic Data Center.

- The arrival "banks" operated as part of United's hub operation. Analysis of the schedule indicates that there are six arrival and departure banks, and flights must be timed within narrow windows to provide suitable connections.
- The coincidence of scheduled departure times in origin cities and their corresponding time zone differences. Table 4 illustrates the relationship between departure times (in local time) in the major geographic regions and their corresponding arrival times at SFO (given the duration of flights from each location). The table shows clearly that the morning peaks at 9 a.m. and 11 a.m. correspond quite closely with the departure times for the "first thing in the morning" flights from many different regions, as well as the scheduled departure windows for international flights originating in Asia. Likewise the 8 p.m. peak coincides with the scheduled departure times for the "end of the day" flights throughout the United States, and the night flights from southern Asia and the Pacific Rim.

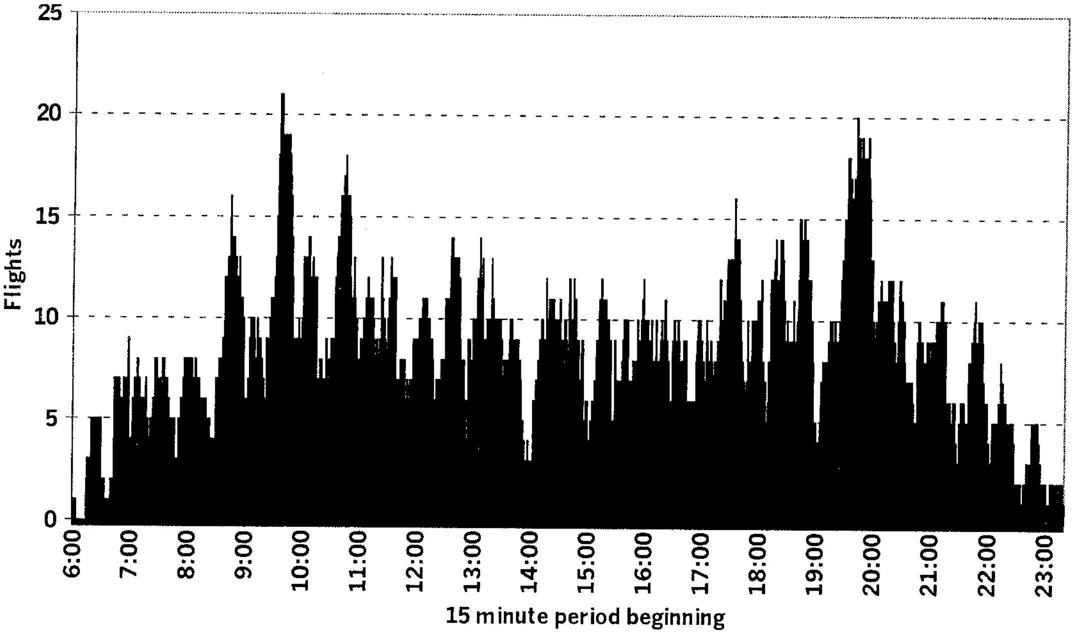
It is important to note that the arrival peak covers the times that the "fog" burns off most mornings. Small changes in the time that burnoff occurs can therefore have a major impact on the delay that occurs on a day characterized by "bad morning weather."

The mix of aircraft using the airport has also been suggested as a possible factor in SFO's delay problem. Because of the different approach speeds of different types of aircraft, a less homogeneous fleet mix might affect the efficiency with which air traffic controllers can manage streams of flights arriving at the airport. And because wake turbulence hazards are greatest between different types of aircraft, FAA-mandated minimum separation requirements vary by aircraft type.

In recent years, the fleet of aircraft at SFO has in fact become more homogeneous, with fewer commuter aircraft and more narrow-body jets. At the same time, however, the aircraft used for about 30 percent of the flights were reclassified into more restrictive categories as a result of the 1996 revision of the FAA's minimum final approach separation requirements. Additional SIMMOD simulations showed, however, that neither of these changes, independently or taken together, have contributed to increased delays at the airport. This result is not surprising given that air traffic controllers can in some cases safely mitigate the effects of these changes. For example, they can pair small aircraft when possible to eliminate potential airborne passing issues, turn small aircraft on shortened final approach courses, or instruct departing small and large aircraft to begin their departure rolls before B-757 or heavy aircraft using parallel runways.



(a)



(b)

FIGURE 2 Flights arriving within next 15 min by minute: (*a*) July 1994; (*b*) July 1998 (source: *Official Airline Guide*, with calculation by the authors).

Role of Delay Propagation

As a major hub airport, SFO provides access to the national route system for many smaller California communities through "feeder" services. At the same time, it serves local travelers in the Bay Area–Los Angeles Basin market, the most traveled air corridor in the world. Both of these markets are operated with very high frequency "shuttle" services. The distances between SFO and the other California airports are sufficiently short that by using short turnaround times, the same aircraft can be used to serve SFO from these cities several times in the same day.

These short turnaround times, combined with the brief flying times characteristic of these short-distance markets, make it potentially difficult for aircraft delayed earlier in the day to make up time on subsequent flight segments, thus allowing delay to "propagate" to these later arrivals. In addition to increasing total delays, propagation can

TABLE 4 Correspondence of Local Departure and SFO Arrival Times

SFO Arrival Time	Local Departure Time (for direct flights)						
	West	Mid	East	Europe	Japan	Hong Kong, Australia, Taiwan	Korea
5:00 AM	3:45 AM	2:30 AM	1:45 AM	2:30 AM	11:50 AM	8:30 AM	10:00 AM
6:00 AM	4:45 AM	3:30 AM	2:45 AM	3:30 AM	12:50 PM	9:30 AM	11:00 AM
7:00 AM	5:45 AM	4:30 AM	3:45 AM	4:30 AM	1:50 PM	10:30 AM	12:00 PM
8:00 AM	6:45 AM	5:30 AM	4:45 AM	5:30 AM	2:50 PM	11:30 AM	1:00 PM
9:00 AM	7:45 AM	6:30 AM	5:45 AM	6:30 AM	3:50 PM	12:30 PM	2:00 PM
10:00 AM	8:45 AM	7:30 AM	6:45 AM	7:30 AM	4:50 PM	1:30 PM	3:00 PM
11:00 AM	9:45 AM	8:30 AM	7:45 AM	8:30 AM	5:50 PM	2:30 PM	4:00 PM
12:00 PM	10:45 AM	9:30 AM	8:45 AM	9:30 AM	6:50 PM	3:30 PM	5:00 PM
1:00 PM	11:45 AM	10:30 AM	9:45 AM	10:30 AM	7:50 PM	4:30 PM	6:00 PM
2:00 PM	12:45 PM	11:30 AM	10:45 AM	11:30 AM	8:50 PM	5:30 PM	7:00 PM
3:00 PM	1:45 PM	12:30 PM	11:45 AM	12:30 PM	9:50 PM	6:30 PM	8:00 PM
4:00 PM	2:45 PM	1:30 PM	12:45 PM	1:30 PM	10:50 PM	7:30 PM	9:00 PM
5:00 PM	3:45 PM	2:30 PM	1:45 PM	2:30 PM	11:50 PM	8:30 PM	10:00 PM
6:00 PM	4:45 PM	3:30 PM	2:45 PM	3:30 PM	12:50 AM	9:30 PM	11:00 PM
7:00 PM	5:45 PM	4:30 PM	3:45 PM	4:30 PM	1:50 AM	10:30 PM	12:00 AM
8:00 PM	6:45 PM	5:30 PM	4:45 PM	5:30 PM	2:50 AM	11:30 PM	1:00 AM
9:00 PM	7:45 PM	6:30 PM	5:45 PM	6:30 PM	3:50 AM	12:30 AM	2:00 AM
10:00 PM	8:45 PM	7:30 PM	6:45 PM	7:30 PM	4:50 AM	1:30 AM	3:00 AM
11:00 PM	9:45 PM	8:30 PM	7:45 PM	8:30 PM	5:50 AM	2:30 AM	4:00 AM
12:00 AM	10:45 PM	9:30 PM	8:45 PM	9:30 PM	6:50 AM	3:30 AM	5:00 AM

SOURCE: *Official Airline Guide* with calculations by the authors, 1999.

cause delays to linger through the day even when bad weather has cleared hours earlier. Because of the significant presence of these shuttle services at SFO (together constituting more than 40 percent of the total daily flights), the extent to which delay propagation may be contributing to SFO's serious delay problem was specifically analyzed.

This was accomplished using detailed operations data obtained from United Airlines and SkyWest Airlines, the operator of United Express services at SFO. These data include the scheduled and actual departure and arrival times of each operation, as well as the tail number of the aircraft used for the flight, allowing one to trace each aircraft through its various flight segments during the course of a day. Analysis of the data confirms that a significant number of both United Shuttle and United Express aircraft are scheduled to return to SFO several times during the same day and that, as a result, an already severe problem is at times being made worse by delay propagation. Most problematic was the propagation of delays between arriving United Shuttle flights on the characteristic foggy days with bad weather only in the morning hours. On some days in the sample, propagation accounted for as much as 30 percent of the delays experienced by these flights.

CONTEXT FOR POLICY ANALYSIS

Before describing the policies formulated as part of the study, it is useful to describe the context of the environment in which any such policy would operate. There are both features and constraints that would be common to any policy, as well as important tradeoffs that may bear on the efficacy of a given policy or its ability to be practically implemented.

One question to consider is, What is the optimal level of congestion delays? At first, the obvious answer might be no delays. But the delay problem at SFO is one of demand exceeding available capacity during periods of bad weather. In good weather conditions, the capacity of the airport is generally sufficient to accommodate the number of scheduled flights. Weather-related congestion delays could be all but eliminated by permanently reducing operations to a level that could be accommodated even with the airport's limited bad-weather capacity, but this would reduce service considerably. And other things being equal, passengers and airlines both prefer more service. So there is an implicit tradeoff between the positive benefits of more air service and the negative effects of flight delays.

Perhaps, then, a policy could be contemplated that would be effective only during bad weather events, or at least during the times of year when delay-causing bad weather most often occurs. But here again, although the weather patterns responsible for the delay problem are known to be generally seasonal in nature, the fact remains that during any season in San Francisco the weather may be poor on one day and fine the next. And from the analysis it is known that even the seasonal effects of the weather are quite varied in their occurrence. So any policy designed to mitigate delays at SFO unavoidably will have some inefficiency associated with it.

In general, pending completion of the runway reconfiguration project, there are basically two broad approaches that could be used to reduce weather-related delays at SFO: decreasing the demand for runway capacity or enhancing the supply of capacity within the existing runway configuration. The latter approach, supply enhancement, is the focus of ongoing research into several new technologies designed to allow more aircraft to be landed safely in bad weather. Analysis suggests, however, that only one of these proposals could be implemented in the short term and even then would provide at best a partial solution. Therefore attention was focused on potential demand-reduction strategies.

Existing Policy Environment and Key Stakeholders

In contemplating potential measures to reduce the demand for runway capacity at SFO, it is important to recognize that in fact demand already is being actively managed during periods of bad weather. The FAA has a number of techniques at its disposal to limit the number of flights to SFO when capacity is constrained to a number that can be landed safely. Most commonly used is the ground delay program (GDP), in which departing aircraft are held on the ground at their origin airport until they can be safely accommodated at SFO. More specifically, through a process known as collaborative decision making (CDM), the FAA and the airlines share information about demand, capacity, and scheduling, such that the airlines are allowed to determine which of their flights will be delayed or cancelled.

It is likewise important to consider that any delay mitigation strategy, like all public policies, will have distributional implications. Some will gain and some will lose, perhaps in varying amounts and perhaps not always in proportion to their interest in or sensitivity to the issue the policy is designed to address. (Even policies relating to "public goods," which economists define as having indivisibility of consumption, have distributional effects. A public park may be free to all, but it will be closer to one person's home than another's. Decisions about national defense likewise may be for the mutual welfare, but a submarine contract may go to the shipyard in Virginia rather than Connecticut, and as has been the case recently, the military bases in certain cities may be closed while others are maintained.) And the complex nature of a major airport in general and the many roles served by SFO in particular mean that there will be many stakeholders involved. SFO is at once a main airport for the residents and businesses in the Bay Area, the primary point of access to the national route system for many smaller West Coast communities (through connecting "feeder" services), a major hub for United Airlines, a principal international gateway, and a large employment center. Parties potentially affected by the delay issue therefore would include, among others,

- Passengers;
- Airlines, among which United is the dominant company in this case;
- The FAA's air traffic control facilities;
- Businesses located at or around the airport;
- Area residents; and
- Actors in the local political process.

These stakeholders, in turn, may have very different interests or concerns. And these interests need to be carefully understood in developing any new policy because any solution to the delay problem will need to address these concerns.

The interests of passengers were analyzed through a series of focus groups with Bay Area frequent flyers, and a survey of departing passengers was conducted at the airport. The interests of passengers from smaller West Coast communities also were specifically examined with a thorough analysis of the flight schedules to assess their dependence on SFO for connection to the national air route system. The kinds of steps these communities have taken to try to improve service to their area also were researched. To better understand the interests of the airlines, each of the carriers operating at SFO was contacted. Personal meetings were held with the management of United Airlines, and the institutional issues (such as union agreements and the like) that might affect the feasibility of certain policies were analyzed. Meetings also were held with officials responsible for managing the air traffic control system to better understand how the CDM process works in practice.

Passengers expressed concern about impacts of delays that extend well beyond the simple extra time incurred, such as missed appointments, increased lodging costs, and the general uncertainty created by a lack of adequate cancellation and delay information. The airlines, by contrast, are most concerned with profit, for which delays will have implications across their entire route network. The FAA has only so many resources to deal with air traffic congestion, which they must likewise address on a national scale. Given these kinds of considerations, it is clear that any policy is likely to affect each stakeholder differently, and aspects that impart benefits to one group might produce costs for another.

The current policy of managing demand with the GDP/CDM policy, for example, favors delays taken on the ground rather than in the air. This saves fuel costs for the airlines, reduces the workload of air traffic controllers, and provides safety benefits for all concerned. On the other hand, if weather clears unexpectedly, aircraft waiting on the ground miles away are unable to take advantage of the now-greater capacity, which may cause higher delays for passengers than would be the case with airborne holding.

The policy is designed to mitigate this problem by assigning ground holds according to geographic proximity to SFO, but this in turn has the effect of concentrating delays and cancellations disproportionately on SFO-bound flights originating in the western United States. Table 5, combining the detailed analyses of the delay and weather data, compares the incidence of delays on West Coast flights with delays in the other regions. It shows that West Coast flights are significantly more likely to suffer delays of an hour or more on days with bad weather in the morning, and that the disparity is even greater on days when the weather is bad all day. Thus the current policy clearly has the effect of distributing costs and benefits even among different groups of passengers.

Given all these considerations, relevant questions in considering alternative policies therefore include the following:

- How will the policy affect the total level of delay?
- Is the policy more or less "efficient" than other policies?
- How will it change the incidence of costs and benefits?

In addition to these general issues associated with the effects of alternative policies, there are also important aspects that will bear on the range of available options as well as any policy's feasibility in implementation. These issues are discussed below.

Legal and Regulatory Environment

Although the U.S. airline industry has historically consisted of private, for-profit carriers, it has at the same time been the subject of significant regulation. Scheduled passenger service began in 1914, just 11 years after the Wright brothers' first flight, but only since the passage of the Airline Deregulation Act of 1978 have modern carriers been able to choose their own route and fare structures. And air

TABLE 5 Comparison of Cancellations and Delay Characteristics by Region

Percentage of Flights Operated That Are:	Good Weather		Bad Morning Weather		Bad Weather All Day	
	West	Other	West	Other	West	Other
"On Time" or Delayed by Less Than One Hour	97%	94%	85%	93%	62%	86%
Delayed by One to Two Hours	2%	4%	13%	5%	23%	5%
Delayed by More Than Two Hours	2%	2%	3%	2%	15%	3%
Total	100%	100%	100%	100%	100%	100%

NOTE: "On time" means that the flight arrived no later than 15 min after its scheduled time of arrival. Columns may not add to 100% due to rounding.
SOURCE: Analysis of U.S. Department of Transportation Airline Service Quality Performance data for calendar year 1999.

traffic control services in the United States are still a government-run enterprise, despite privatization efforts in some other countries.

Airports, likewise, have traditionally been under government control, subject both to legal mandates and to local political prerogatives. At a few airports, a federal regulation known as the High-Density Rule has limited the scope of airport operations through slot restrictions that effectively specify a maximum number of arrivals. Perimeter rules have been adopted at a few other airports, limiting traffic by capping the distance to which departing flights can travel. And one airport—John Wayne Airport in Orange County, California—has adopted a simple limit on the total number of passenger enplanements. Recently, however, the trend has been to relax rather than expand these regulations.

Congestion-sensitive pricing of runway access has also been proposed, but no program has yet been implemented. Although congestion pricing is eminently attractive to economists because of its efficiency benefits, barriers to its feasibility remain significant. Being government (or at least quasi-government) enterprises, airports are ostensibly prohibited from making a profit from their operations. And even if they weren't, what would they do with the money? And how would the pricing mechanism be designed? The latter is particularly important given that federal law requires airports to provide "equal access" for any aeronautical use without discrimination. Even more problematic in the case of SFO is that existing long-term use agreements between the airport and air carriers would preclude anything other than the current fee structure for a number of years. For these reasons, congestion pricing was excluded from the analysis. The types of strategies focused on are described in the following section.

SPECIFIC STRATEGIES EXAMINED

A set of spreadsheet-based, deterministic queuing models were developed specifically for this project and used to assess the delay impacts of various demand-reduction strategies. These models incorporate the actual schedule of arriving flights at the airport and allow flights to be systematically or individually removed from the schedule or moved to other time periods. This made it possible to test a wide range of alternatives. The models compute the effect of schedule changes not only on total delays but also on the number of flights and seats offered. And changes in delays can be assessed at the level of the individual flight, allowing a very thorough examination of the effects of each policy on service quality and the benefits to travelers from different cities or regions, using different airlines, or even different aircraft types.

Restricted midday service and aircraft upgauging, which were among the most closely analyzed policies, will be described for illustrative purposes.

- Restricted midday service. Between 8:30 a.m. and 1 p.m., this policy would prohibit the arrival of commuter flights and limit the noncommuter arrivals of any carrier to one flight per hour per city.
- Aircraft upgauging. This policy would be intended to cause the use of fewer, larger aircraft on certain routes with very high service frequency. It was modeled assuming a minimum aircraft size of 170 seats on routes currently with 15 or more flights or 50 seats on commuter routes with 10 or more flights per day. Flights were removed from the schedule based on the assumption that the total number of seats would remain constant.

Of these two policies, the first was estimated to be more effective at reducing weather-related congestion delays at SFO. And it would likely be highly efficient because most of the flights removed would be those using very small aircraft, with commuter operations constituting 18 percent of the flights at SFO but only 3 percent of the passengers. However, this policy also represented a significant reduction in service, in effect eliminating all morning flights to several smaller West Coast communities. It would also make it more difficult for travelers from these smaller cities to connect to destinations outside the region. And such a large restriction on the operations of commuter flights could have significant negative impacts on the profitability of SkyWest Airlines, the dominant commuter carrier.

The upgauging proposal, although not accomplishing quite as much delay reduction, would essentially keep the number of seats offered constant. The cities of Los Angeles, Eureka, Monterey, Sacramento, and Fresno would each lose some scheduled flights, but the remaining services would likely be more reliable. These cities tend to suffer disproportionate amounts of delays and cancellations under the current system because it focuses delays on the West Coast, and thus these cities would likely benefit significantly from the overall delay reduction. And because of the increased reliability, even with fewer scheduled flights they might not experience an overall reduction in service. Moreover, because the need for smaller outlying communities to maintain access to the national air route system had been identified as an important concern, it would ensure that each of the latter four cities would maintain service at least sufficient to meet each of United's six connecting banks. The effect on airline revenue is not clear, but the increase in aircraft size would certainly involve important cost considerations. The estimated impacts of the two policies are summarized in Table 6.

TABLE 6 Summary of Results for Selected Policy Alternatives

Policy	Flights Eliminated		Seats Eliminated		Simulated Hours of Delay 1997-1999
	Number	% of Total	Number	% of Total	
Base case (no cancellations)	0	0%	0	0%	91,074
Current GDP/CDM policy	35	6.2%	4,514	5.6%	40,981
Restricted midday service	47	8.4%	2,872	3.6%	19,787
Aircraft upgauging	46	8.2%	0	0%	30,313

NOTE: Simulated delay impacts represent effect of actual weather conditions during 1997–1999 period. Base case represents simulated effect of full schedule with no cancellations. Delay reduction of current GDP/CDM process simulated using pattern of actual cancellations on Dec. 13, 1998. All simulations conducted using SFO arrival schedule of July 5, 2000.
SOURCE: Calculations by the authors, 2000.

The table shows the approximate number of flights and seats that would be eliminated by each of the two policies, as well as the estimated number of hours of delay simulated with the model. Each figure should be compared with the base case, which represents the output of the model assuming that every flight in the schedule is flown, without any cancellations. For comparison, an estimate also is shown for the current *de facto* demand management strategy using the GDP/CDM process. Because there were only very limited data on the actual flights currently cancelled (the individual flight numbers as distinct from simply the total number of flights), this is only a rough estimate. However, it illustrates that a number of flights are now being cancelled under CDM and that, like the other policies, these cancellations serve to reduce delay at the airport from what it would be otherwise.

SUMMARY AND RECOMMENDATIONS

San Francisco International Airport is typical of many large airports in that rapid growth in air travel has outpaced the available runway capacity, leading to serious delays. At the same time, SFO represents a unique circumstance because of the role of its local climate, and thus it requires careful analysis to address its delay situation. The weather patterns contributing to delays at SFO and the role played by the many facets of aircraft operations at the airport have been examined. This paper has summarized some of the results of these analyses and described the key issues in approaching any formulation of policies meant to address the delays caused by airport congestion. The types of specific policies examined and their estimated impacts have been described.

Based on this research, the following recommendations were made to SFO management:

- Seek the implementation of the aircraft upgauging policy described above;
- Work with the airlines to increase the turnaround times on certain high-frequency services to reduce the propagation of delays; and
- Investigate ways in which better and more timely delay and cancellation information can be conveyed to passengers.

Based on these recommendations, the airport began the formal procedure to implement the upgauging strategy through a local congestion delay rule, using the FAA's Part 161 Process. At the same time, it continued to maintain a dialogue with the airlines in hopes of achieving the same result through nonregulatory means.

On June 7, 2000, the airport announced a tentative agreement with United Airlines, SFO's dominant carrier, to reduce delays through a series of voluntary but targeted schedule reductions. The authors' analyses of the delay-reduction potential of the various strategies, including United's proposed changes, were instrumental in helping the parties reach the agreement. Although this agreement is meant to address the specific problems associated with SFO's local conditions, the types of analyses conducted in this study could easily be applied to a broad range of policy issues at any major airport and solutions likewise developed to meet each local need.

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1. Charles River Associates Incorporated and The John F. Brown Company, Inc. *Reducing Weather-Related Delays and Cancellations at San Francisco International Airport.* San Francisco International Airport, San Francisco, Calif., April 2000. [The full report may be obtained by contacting the SFO Public Affairs Office at (650) 821-4000.]

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Evaluating Cost-Effectiveness of an Air Traffic Management System for Europe

Development and Application of Methodological Framework

Konstantinos G. Zografos and Ioanna M. Giannouli

In response to growing air transport congestion, new air traffic management (ATM) concepts have been put forward to ameliorate existing problems. By their nature, ATM systems are highly complex, and their development and implementation require substantial financial resources. Moreover, the introduction of a new ATM system generates tangible as well as intangible benefits and costs. Therefore, a methodological framework capable of addressing all specific characteristics of the ATM system cost-effectiveness evaluation should be developed. The objective of this paper is twofold: first, to develop a methodological framework for evaluating the TORCH system (i.e., a new ATM concept for Europe), and second, to present the results of the application of the proposed framework for assessing the cost-effectiveness of the TORCH system. The proposed methodology was applied with the help of a panel of European ATM experts. The application results are intuitively appealing and indicate a strong convergence of the expert opinions concerning the most preferable ATM system. More specifically, the results of the evaluation suggest that an investment in TORCH will improve the safety, operational, and environmental performance of the ATM system as well as the working conditions of the air traffic controllers, and at the same time, the TORCH system will be marginally cost-effective.

In recent years European air traffic is growing at increasingly high rates. Air traffic congestion has a major impact on all stakeholders involved in the provision of air transport services and the economy in general. In response to growing air transport congestion, new air traffic management (ATM) concepts have been put forward to ameliorate existing problems. ATM systems are highly complex, and their development and implementation require substantial financial resources. Furthermore, the introduction of new ATM systems generates new training requirements for the personnel operating them. Therefore, it is important to be able to evaluate the expected impacts that will be generated by the introduction of new ATM systems and assess their cost-effectiveness before final investment decisions are made (*1*). Aside from technical complexity, other reasons exacerbating the degree of difficulty associated with the evaluation of an ATM system are

- The substantial number of stakeholders involved in and affected by the ATM system;
- The existence of different points of view among the stakeholders;
- The existence of multiple criteria expressing the effectiveness and the costs of an ATM system, which may be qualitatively or quantitatively measured; and
- The difficulty of obtaining reliable system performance measurements.

Therefore, a methodological approach capable of addressing all the above-mentioned ATM system evaluation characteristics should be developed.

The objective of this paper is twofold: first, to develop a methodological framework for evaluating the TORCH system (*2*) (i.e., a new ATM concept for Europe), and second, to present the results of the application of the proposed framework for assessing cost-effectiveness of the TORCH system (*2*).

This paper consists of the following sections: a brief presentation of the TORCH system, the methodological approach used to perform the cost-effectiveness analysis, the results of the cost-effectiveness analysis, and concluding remarks about the methodology and the cost-effectiveness of the proposed ATM system.

TORCH OPERATIONAL CONCEPT

The TORCH concept refers to the European ATM system that will be implemented from the year 2005 onward. The following description is an excerpt from a report (*2*) that provides a comprehensive description of the TORCH concept. An overview of the characteristics of the proposed system follows.

The TORCH operational concept focuses on improvements in airspace management and flow management. These improvements will allow TORCH to meet the objectives of increasing safety and capacity while optimizing the economics of the ATM system. TORCH proposes a layered planning process (*2*) based on a more flexible use of the airspace and with a greater involvement of the ATM actors through optimizing the available resources instead of constraining demand.

The TORCH concept shifts the ATM control philosophy from event management to strictly applied time management of flights supported by the daily operational plan (DOP) if resources are operated close to their maximum capacity. The most significant TORCH proposal is to develop a DOP through the dynamic use of collaborative decision making (CDM). This plan is developed on the basis of the information contained in the strategic plan, established 1 year in advance of the day of operation. Until the day of operation, the layered planning process will continuously receive real-time updates to changing parameters (rolling planning), making the decision-making loop more sensitive to stakeholder needs. Using CDM procedures, the DOP will be updated to create a comprehensive picture of the current traffic situation, taking into account real-time changes that can affect the stakeholders' expectations.

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The DOP process will improve the tactical planning phase, bridging the current gap between planning—central flow management unit (CFMU)—and execution—air traffic control (ATC). The increased accuracy and dynamic planning enabled by the DOP will increase efficiency, in the sense of improved use of available physical capacity.

Terminal area (TMA) sequencing will match the planned approach and departure sequences to optimize TMA resources, through coordination among the stakeholders involved in the process, such as airports.

During the TORCH time frame, responsibility for separation assurance may be partially delegated to the aircrews of suitably equipped aircraft. Conflicts will be detected by the ground system, which will propose conflict resolution strategies. Hazard assessment will be based on improved safety-net functions [i.e., short-term collision alert (STCA), area proximity warning (APW), minimum safe altitude warning (MSAW), and airborne collision avoidance system (ACAS)].

Aircraft operators will become more involved in planning and will make decisions together with ATC and the CFMU. They will negotiate their plans during the planning phase and exchange information with other stakeholders. Real-time data will be used to optimize fleet operations. Schedules and routes will be closer to user preferences, improving the overall predictability of the system.

Airport operations will be more integrated in the overall ATM process than at present. Air traffic flow management (ATFM) measures and airport capacities will be linked during all planning phases. Coordination with the en-route planning phase will support uninterrupted gate-to-gate operations.

The TORCH operational concept has been divided into clusters of elements. Each cluster comprises elements related to specific functions or a time frame. Five "vertical" clusters have been defined as follows:

- Cluster 1, From Strategic Planning to Real-Time Optimization, includes the following functions: airspace plan development, demand and capacity determination, operational plan development and implementation, and real-time optimization.
- Cluster 2, Local Tactical Planning, includes en route planning and TMA sequencing.
- Cluster 3, Tactical Traffic Control, involves separation assurance and hazard assessment.
- Cluster 4, Airline Operations, includes airline operations planning, aircraft flight management gate-to-gate, and aircraft operator (AO) flight control.
- Cluster 5, Airport Operations, consists of airport strategic planning and airport operations management and control.

In addition, two "horizontal clusters" are considered: Performance Management and Information Management. Both elements provide support to the other five clusters. A graphical representation of the operational concept of the proposed ATM system is shown in Figure 1.

METHODOLOGICAL FRAMEWORK FOR COST-EFFECTIVENESS ANALYSIS OF AN ATM SYSTEM

The evaluation of the new concept proposed for the improvement of the European ATM system necessitates the development of a methodological framework able to address the requirements imposed by the complexity characterizing the ATM system. More specifically, the methodology that will be used for the evaluation of the TORCH system should be able to

1. Consider multiple criteria expressing the evaluation objectives of all groups and individuals (stakeholders) involved in and affected by the performance of the ATM system,
2. Quantify the evaluation criteria expressing both the tangible and the intangible benefits and costs of the system,
3. Assess the relative importance of the various evaluation criteria,
4. Synthesize the opinions of the various stakeholders to determine the most preferable "compromise" solution, and
5. Cope with the inherent uncertainty associated with the estimation of benefits and costs by performing sensitivity analysis.

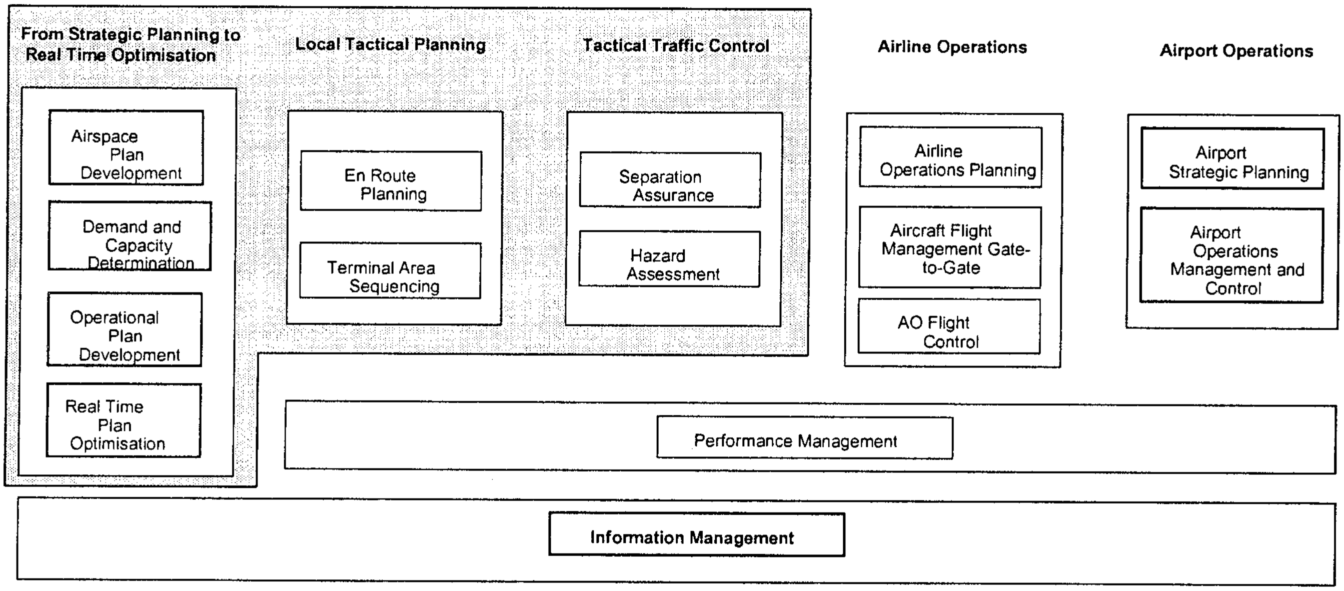


FIGURE 1 Clusters of the elements.

The methodological framework (*3*) proposed for the cost-effectiveness evaluation of the TORCH system is shown in Figure 2.

The cornerstone of the proposed evaluation framework is the determination of the ATM system stakeholders. For the case of the European ATM system, the following stakeholders were identified:

- Air service management (ASM)/air traffic flow management organization,
- Airline association,
- General aviation association,
- Air traffic management service providers,
- Air traffic management equipment suppliers,
- Airport authorities,
- Research institutes,
- Corporate aviation,
- Military operations,
- Passenger association, and
- Hotel and tourism industry.

It is important to stress that, due to the spatial coverage provided by the ATM system, the various stakeholders represent not only their organizations but also their geographic constituencies. The multiple actors of the ATM system define the needs of the users of the ATM system. These needs in turn are translated into ATM system functionalities through their incorporation into the ATM system design. In addition to the system functionalities, user needs also define the objectives, criteria, and indicators that should be used to evaluate the cost-effectiveness of the proposed system.

The performance of any cost-effectiveness analysis requires the identification of the various indicators that will be used to evaluate the effectiveness and the costs of the alternative ATM systems.

Based on the above, a number of indicators have been identified to quantify effectiveness and cost criteria. The identified indicators are provided in Tables 1 and 2.

Identification of the Appropriate Evaluation Technique for Cost-Effectiveness Assessment

The analytical hierarchy process (AHP) was selected for assessing the cost-effectiveness of the TORCH system (*4*). It was selected because it fulfills all the requirements for the evaluation of a new ATM system. The AHP provides a practical way to deal quantitatively with complex decision-making problems and an effective framework for group decision making (*5*) (i.e., a decision-making process involving multiple decision makers).

The AHP is based on three principles: (*a*) the principle of constructing hierarchies, (*b*) the principle of establishing priorities, and (*c*) the principle of logical consistency. According to the method, a complex decision-making problem is decomposed hierarchically into its components. After the hierarchical decomposition of the problem has been completed, a matrix of pairwise comparisons, expressing the relative importance of the elements in a given level of the hierarchy with respect to the elements in the level immediately above it, is constructed.

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1k} & \cdots & a_{1n} \\ \cdot & & \cdot & & \cdot \\ a_{l1} & & a_{lk} & & a_{ln} \\ \cdot & & \cdot & & \cdot \\ a_{n1} & \cdots & a_{nk} & \cdots & a_{nn} \end{bmatrix}$$

The resulting pairwise comparisons matrix is positive and reciprocal (that is, $a_{ij} > 0$ and $a_{ij} = 1/a_{ji}$). Finally the selection of the most preferred alternative is made based on the values of the priority vector of the lowest level of hierarchy.

One of the major advantages of AHP is the capability to identify errors in judgment and evaluate the consistency of the evaluators by calculating an index called consistency ratio (CR). The calculation of CR, with CI as the consistency index, is described by the following equation:

$$CR = \frac{CI}{RI}$$

where

$$CI = \frac{\lambda_{\max} - n}{n - 1};$$

$\lambda_{\max}$ = maximum eigenvalue of matrix A;
n = matrix dimension; and

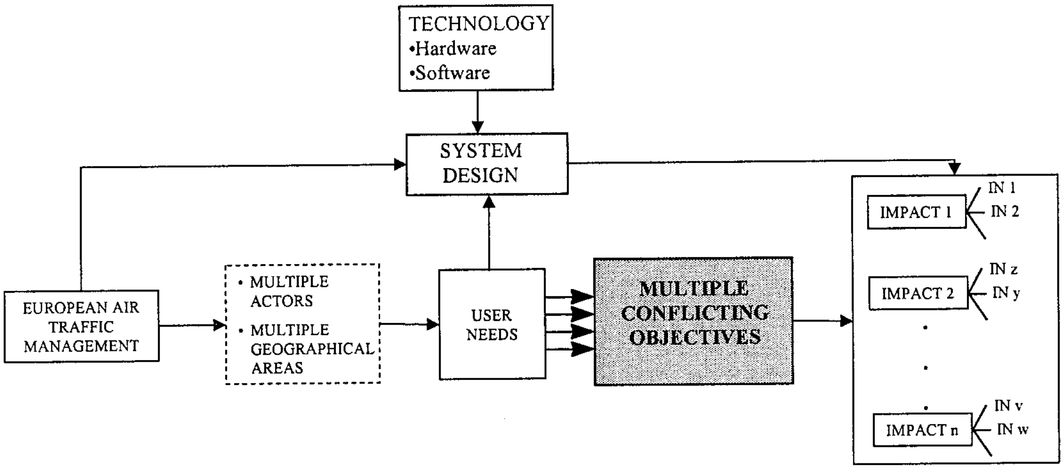


FIGURE 2 Methodological framework for TORCH cost-effectiveness evaluation.

TABLE 1 Indicators Measuring Potential Benefits

Effectiveness	Indicators	Abbreviation
Safety	Number of Accidents per Year	NOACC (SI1)
	Number of Air Misses per Year	NOAIRM (SI2)
	Number of Fatalities per Year	NOFACIL (SI3)
	Number of Airport-related Accidents per Year	NOAIRP (SI4)
	Number of Airport-related Incidents per Year	NOAIRI (SI5)
System Performance	Percentage Deviation of Actual Arrival Time as Compared with Published Scheduled Time	ACTARRI (SPI1)
	Percentage Deviation of En-Route Flight Time as Compared with Scheduled Time	ENROUTE (SPI2)
	Number of Flight Plan Requests Accepted Without Changes over the Total Flight Plan Requests	FLIREQUE (SPI3)
	Number of Aircraft Movements at an Airport Under the Worst Visibility Level	NOA/C (SPI4)
	Degree of Harmonization of the ATM Level Among EU Member Countries	HARMONI (SPI5)
Environment	Fuel Consumption per Passenger per km	FUELCON (EI1)
	Average Level of Noise of Departing/Arriving Flights	NOISE (EI2)
	Maximum Level of Noise of Departing/Arriving Flights	MAXNOISE (EI3)
	Average Emission per Ton of Fuel Consumed	EMISSION (EI4)
Working Conditions	Workload Level	WORKLOAD (WC1)
	Stress Level	STRESSL (WC2)
	Job Satisfaction	SATISFA (WC3)
	Training Needed for the Effective Use of the Required Tools/Equipment	TOOLS (WC4)

RI = random index computed as follows: for each size of matrix n, random matrices are generated and their mean CI value, called RI, was computed.

CR values greater than 0.10 declare inconsistency in judgment(s) and require the decision maker to reduce inconsistencies by revising judgments.

The main advantages of the AHP method are that it

- Is simple to understand and apply,
- Provides weight assignment features,
- Offers the ability to perform sensitivity analysis,
- Features hierarchical criteria analysis, and
- Has the ability to gauge the relative importance (weight) of individual responses in a nonhomogeneous panel of judges.

The goal of the analytic hierarchy process model for the needs of the cost-effectiveness assessment of an ATM system is to rank the competing alternatives (i.e., TORCH system and the existing BASELINE ATM systems) in terms of their relative cost and effectiveness.

Because the goal of the evaluation exercise is to compare the TORCH and BASELINE systems in terms of their cost-effectiveness, it is necessary to construct two distinct hierarchies, one for assessing the relative effectiveness and one for assessing the relative costs. The AHP model for ranking the alternatives in terms of their effectiveness is illustrated in Figure 3. The respective AHP model for the cost comparison of the two alternatives is presented in Figure 4.

The effectiveness hierarchy (see Figure 3) consists of four levels. The first level includes the assessment goal (ranking the two alternative systems in terms of their effectiveness). The second level consists of the various categories of impacts, and the third level involves the indicators measuring the system performance in terms of the different categories of impacts. Finally, the fourth level of the hierarchy involves the two alternative systems under evaluation—TORCH and BASELINE.

The cost hierarchy (see Figure 4) consists of three levels. The first level includes the assessment goal (ranking the alternative two systems in terms of their cost). The second level consists of the various cost categories (criteria), and the third level involves the two alternative systems under evaluation—TORCH and BASELINE.

As can be seen in Table 2 and in Figures 3 and 4, the cost indicators used include all costs involved in the acquisition and operation of the ATM system per se. Cost items derived as a result of the system performance (i.e., cost of delays, fuel consumption, and so on) have been included as measures of the system effectiveness. Stated otherwise, in the evaluation process the savings in delays are considered as an indicator of the system effectiveness instead of using absolute delays as a system cost. Furthermore, an assumption was made that the two systems (BASELINE and TORCH) are equally reliable and that the TORCH system will be designed in such a way as to achieve its technical performance objectives.

Data Collection

Assessments of both the effectiveness and the cost of the TORCH system were based on the results of an expert opinion survey conducted

TABLE 2 Indicators Measuring Costs

Cost Indicators	Abbreviation
Acquisition Cost	ACQUISIT
Training Cost	TRAINING
Transition Cost	TRANSIT
Operational Cost	OPERAT
Maintenance Cost	MAINTEN

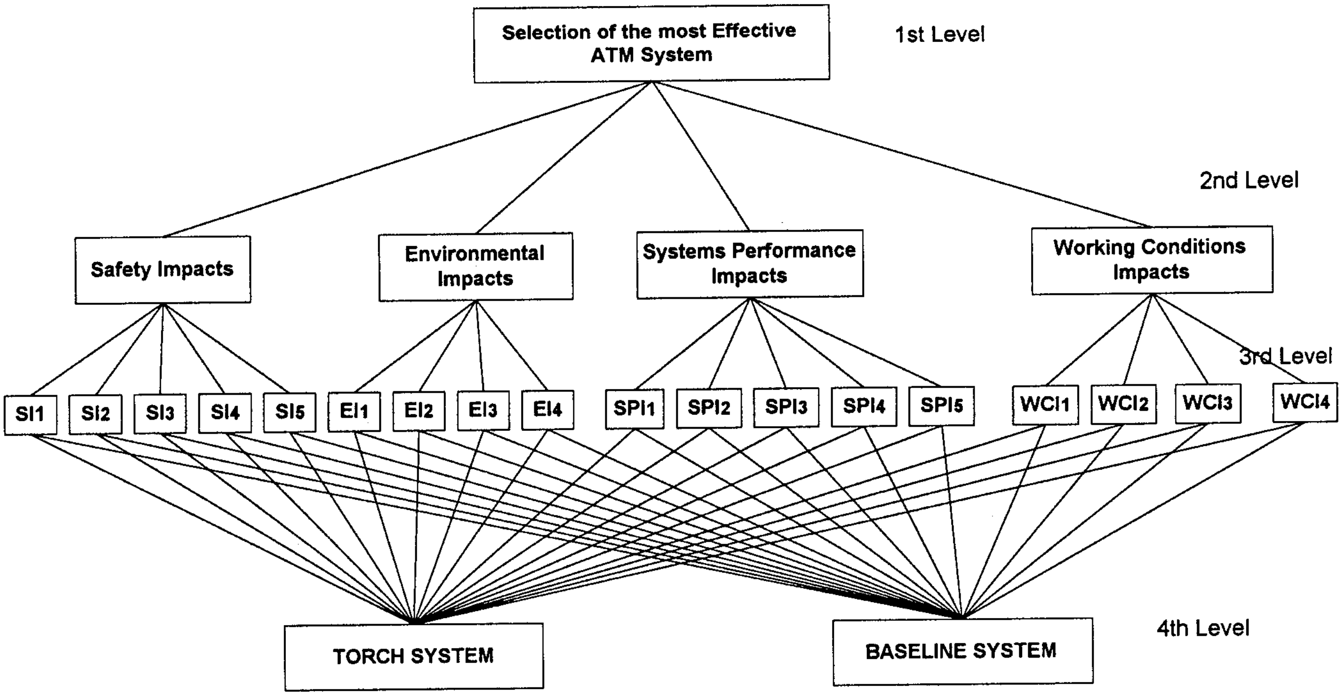


FIGURE 3 Hierarchical decomposition of ATM system effectiveness.

within the framework of the TORCH project [the Directorate General for Transport of the European Commission (DG TREN)] (*6*). Twenty-four experts representing most of the stakeholders of the European ATM system participated in the survey. The composition of the panel of experts in terms of their affiliation is provided in Table 3.

The members of the expert panel were asked to self-rate their expertise in relation to the issues they were called on to assess. The self-rated expertise was expressed on a scale of 1 to 5, with 1 standing for minimal expertise and 5 for very high expertise. Figure 5 presents a summary of the self-rated expertise of the panel members.

As can be seen in Figure 5, the overwhelming majority of the panel participants (80 percent) had substantial self-rated expertise.

The survey took place during a 2-day meeting in Brussels. Before the completion of the relevant AHP questionnaire, the experts were briefed on the properties of the method, the characteristics of both the BASELINE and the TORCH systems, and the questionnaire content. Specially trained personnel assisted the experts (one interviewer for every three experts) in completing the questionnaire. The AHP results were presented to the experts the second day of the meeting in order to get their feedback. The AHP questionnaire included two parts. The first part involved questions related to the assessment

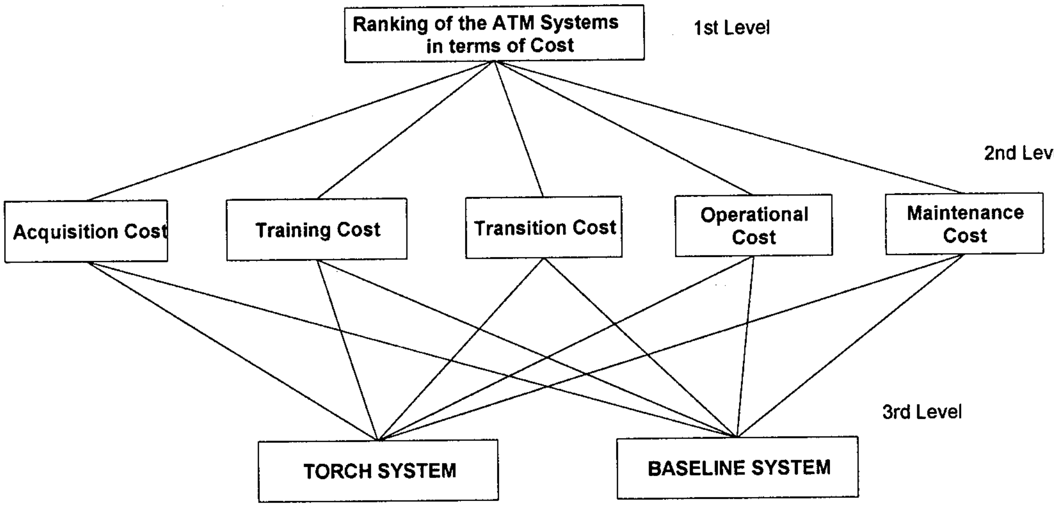


FIGURE 4 Hierarchical decomposition of ATM system costs.

TABLE 3 Composition of the Expert Panel

Organization	No. of Participants
ATM Service Providers	2
Airport Operators/ATM Service Providers	2
ASM ATFM Organization	7
Airline Association	1
General Aviation Association	1
Research Institutes	4
ATM Equipment Suppliers	7

of the relative effectiveness of the two systems under consideration. The second part included questions related to the assessment of the relative cost of the two systems.

Concerning the estimation of the ATM system effectiveness, the experts were asked to provide their judgment in the form of pairwise comparisons of the relative importance of each element located at a given level of the hierarchy of Figure 3 in influencing each element of the hierarchy located at the next higher level.

Thus, all elements of the second level of the hierarchy (i.e., impacts) were compared in pairs in terms of their relative importance in determining the overall effectiveness of the ATM system (first level of the hierarchy). Questions in the form "How important do you consider impact *i* as compared with impact *j* in determining the overall effectiveness of an ATM system?" were used to elicit the opinion of the experts.

Likewise, all elements of the third level of the hierarchy (i.e., indicators) were compared in pairs in terms of their relative importance in determining the magnitude of the corresponding impact located at the second level of the hierarchy. Questions in the form "How important do you consider indicator *i* as compared with indicator *j* in determining the magnitude of impact *k*?" were used to elicit the expert opinions.

Finally, the two ATM systems under comparison, located at the fourth level of the hierarchy of Figure 3, were compared in terms of their relative performance with respect to all indicators located at the third level of the hierarchy. Questions in the form "How is the TORCH system expected to perform in terms of indicator *i* as compared with the baseline ATM system?" were used to elicit the expert opinions.

All comparisons made by the experts were expressed on a nine-point ratio scale. The definition of the numerical values of the nine-point scale is provided in Table 4.

The same approach was used to assess the relative cost performance of the two ATM systems under comparison. In this case the experts were asked to express their judgment on (*a*) the relative contribution of each cost criterion to the overall ATM system cost and (*b*) the relative performance of each competing system in terms of all cost criteria.

Data Analysis

The analysis of the results was performed in two stages. At the first stage, analysis of the data expressing the expert judgment was performed by considering all responses together (see Figure 6). The objective of the analysis was to rank the TORCH and the BASELINE systems in terms of their effectiveness and cost. Furthermore, the relative importance of the various criteria and indicators was also assessed. Sensitivity analysis was performed in order to determine the robustness of the ranking results in terms of the relative importance of the criteria. The analysis of the first stage was completed by the calculation of the cost-effectiveness ratio of the TORCH and BASELINE systems.

The second stage of analysis involved the clustering of the experts into groups representing the interests of the major stakeholders of the ATM system. The following stakeholder groups were identified among the participating experts: ATM service providers, ASM/ATFM organization, ATM equipment suppliers, general aviation association, airline association, research institutes, and airport operators.

Following the identification of the groups of stakeholders, the same type of analysis used in the first stage was performed to identify similarities and differences in the ranking of the alternatives among the various groups of experts. An overall synthesis of the results was also performed in order to draw final conclusions about (*a*) the ranking of the TORCH and BASELINE systems in terms of their effectiveness, cost, and cost-effectiveness ratio, and (*b*) the relative importance of the various criteria measuring the cost-effectiveness of ATM systems. Figure 6 illustrates the various steps involved in the analysis of the AHP questionnaires.

The analysis of the collected data was made with the assistance of Expert Choice Inc. (*7*). Two sets of graphs are used to summarize the results of the analysis. In the first set (Figures 7–14), bar charts are used to illustrate either the ranking of the alternative systems, or the relative importance of the various assessment criteria or indicators expressing them. For example, Figure 7 indicates the ranking of the two ATM systems in terms of their effectiveness for the ungrouped data, whereas Figure 8 indicates the relative importance of the effectiveness assessment criteria for the ungrouped set of data. The second set of graphs (see Figures 15 and 16) illustrates the performance of the two systems under evaluation over the assessment criteria. The horizontal

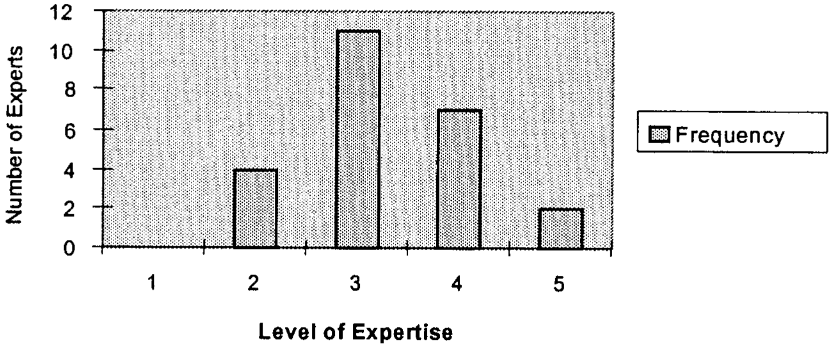


FIGURE 5 Self-rated expertise of panel members.

TABLE 4 AHP Ratio Scale

Number	Relative Importance
1	Equal importance
3	Moderate importance of one over another
5	Essential or strong importance of one over another
7	Very strong importance of one over another
9	Extreme importance of one over another
2,4,6,8	Intermediate values between the two adjacent judgments

axis of Figure 15 represents the four major effectiveness criteria (i.e., safety, performance, environment, and working conditions); the horizontal axis of Figure 16 represents the six cost criteria. The left side axis of both Figures 15 and 16 represents the relative importance of the evaluation criteria; the right side axis represents the performance of the alternative systems on the evaluation criteria. The two lines (i.e., a dotted line and a solid line) indicate the fluctuation of the performance of each alternative system in relation to the relative importance of each assessment criterion.

The results derived through the application of the proposed methodological framework are provided in the following paragraphs.

UNGROUPED COST-EFFECTIVENESS ANALYSIS

Benefits

The analysis of ungrouped data revealed that the TORCH system is far more preferable than the BASELINE system in terms of effectiveness. As Figure 7 suggests, the TORCH system outperforms the BASELINE system by a 2-to-1 ratio. Furthermore, the overall inconsistency of the expert judgments regarding the ranking of the two systems was very low (2 percent), which suggests that the ranking of the two alternative systems is valid in terms of the logical consistency of the pairwise comparisons provided by the participating experts.

The analysis of the relative importance of the criteria measuring the effectiveness of the TORCH and BASELINE systems suggests that safety was considered to be the most important criterion for the ranking of the two systems. As Figure 8 suggests, safety accounts for about 65 percent of the impacts, whereas all other criteria (i.e., environment, system performance, and working conditions) account for the remaining 35 percent. Following safety, the most important criterion was system performance, accounting for 13.5 percent, closely followed by working conditions, 11.5 percent. Finally, the

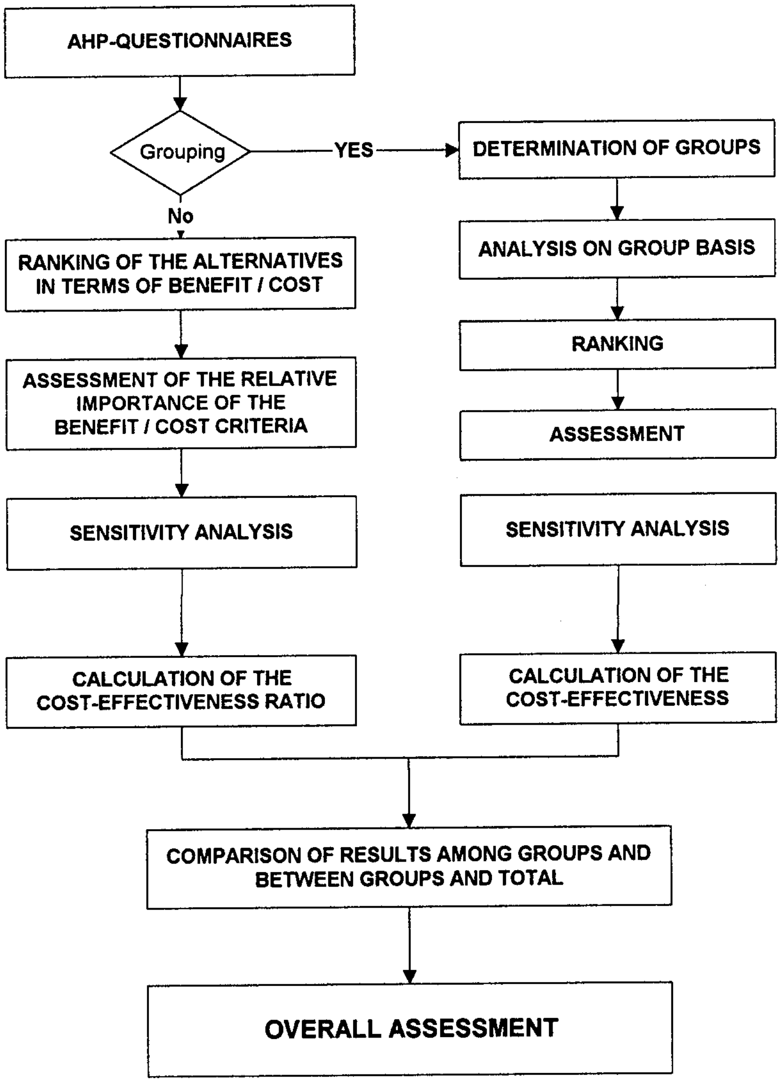


FIGURE 6 Methodological approach for analyzing AHP questionnaires.

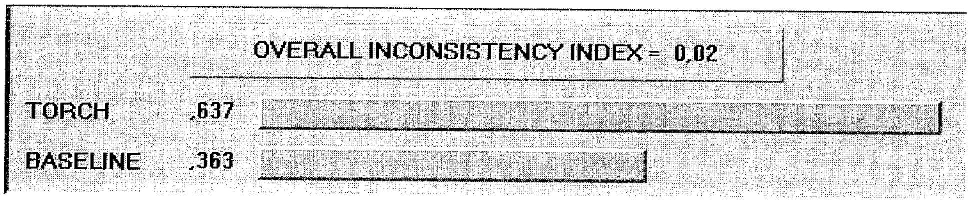


FIGURE 7 Ranking of alternative systems in terms of effectiveness (ungrouped data).

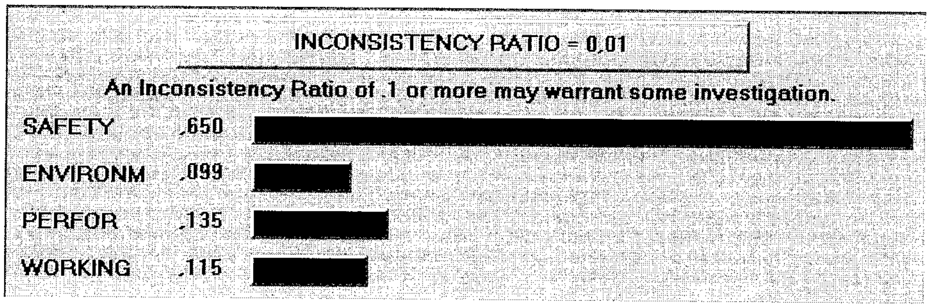


FIGURE 8 Relative importance of effectiveness assessment criteria (ungrouped data).

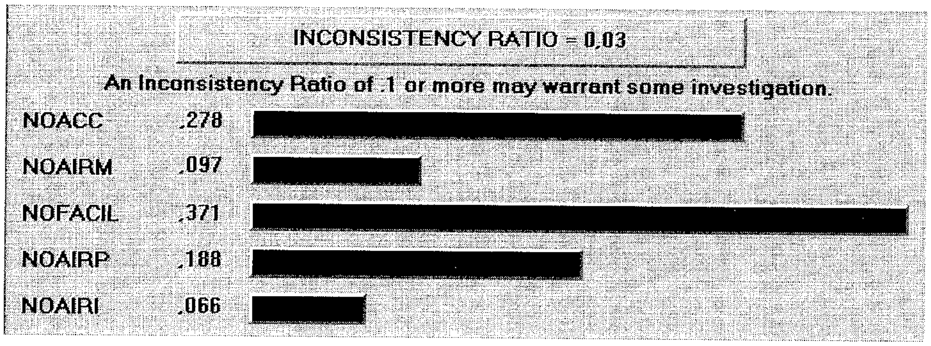


FIGURE 9 Relative importance of safety indicators (ungrouped data).

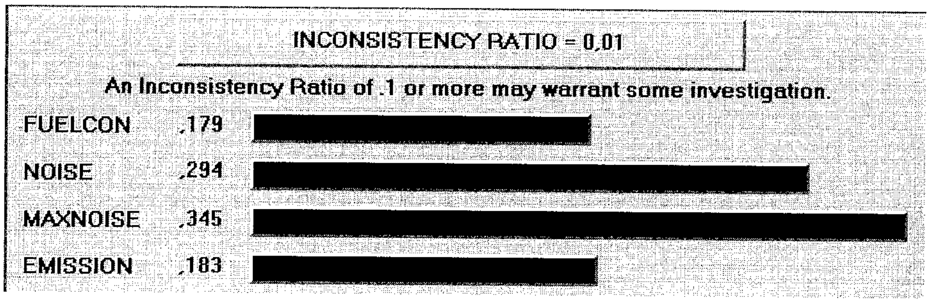
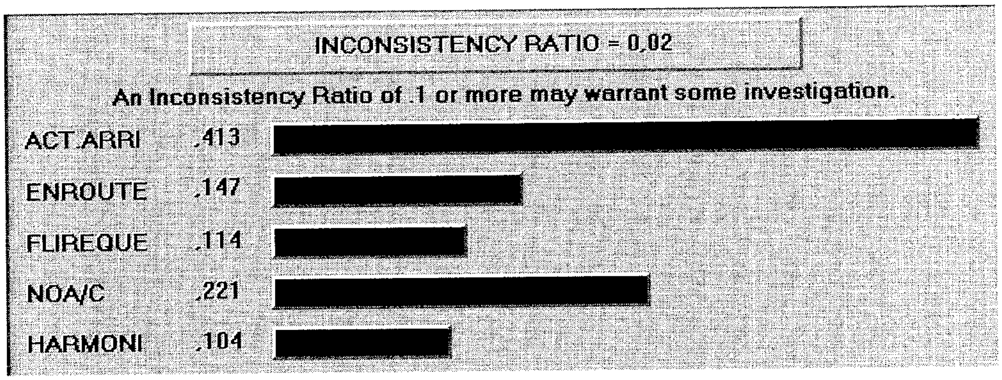


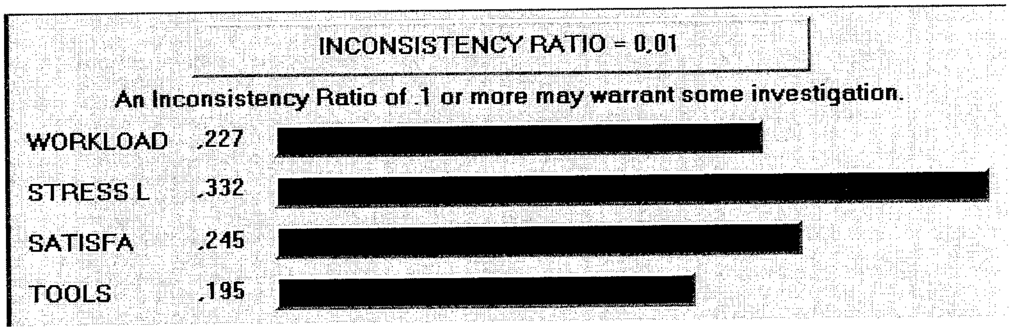
FIGURE 10 Relative importance of environmental impact indicators (ungrouped data).


INCONSISTENCY RATIO = 0.02

An Inconsistency Ratio of .1 or more may warrant some investigation.

ACT.ARRI	.413
ENROUTE	.147
FLIREQUE	.114
NOA/C	.221
HARMONI	.104

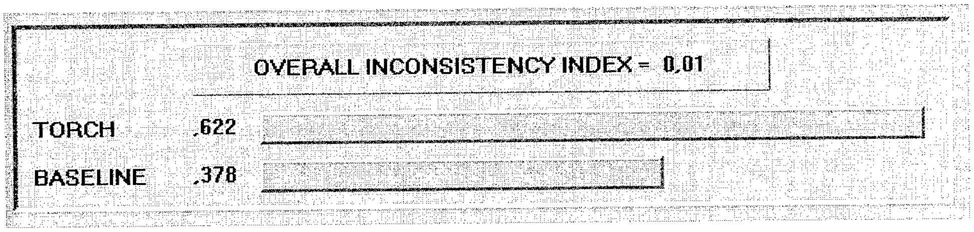
FIGURE 11 Relative importance of system-performance indicators (ungrouped data).


INCONSISTENCY RATIO = 0.01

An Inconsistency Ratio of .1 or more may warrant some investigation.

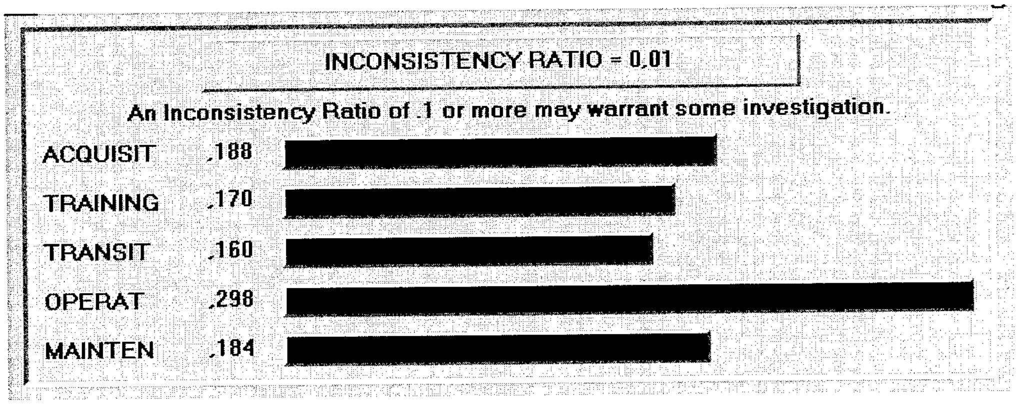
WORKLOAD	.227
STRESS L	.332
SATISFA	.245
TOOLS	.195

FIGURE 12 Relative importance of working-conditions indicators (ungrouped data).


OVERALL INCONSISTENCY INDEX = 0.01

TORCH	.622
BASELINE	.378

FIGURE 13 Ranking of alternative systems in terms of cost.


INCONSISTENCY RATIO = 0.01

An Inconsistency Ratio of .1 or more may warrant some investigation.

ACQUISIT	.188
TRAINING	.170
TRANSIT	.160
OPERAT	.298
MAINTEN	.184

FIGURE 14 Relative importance of cost criteria (ungrouped data).

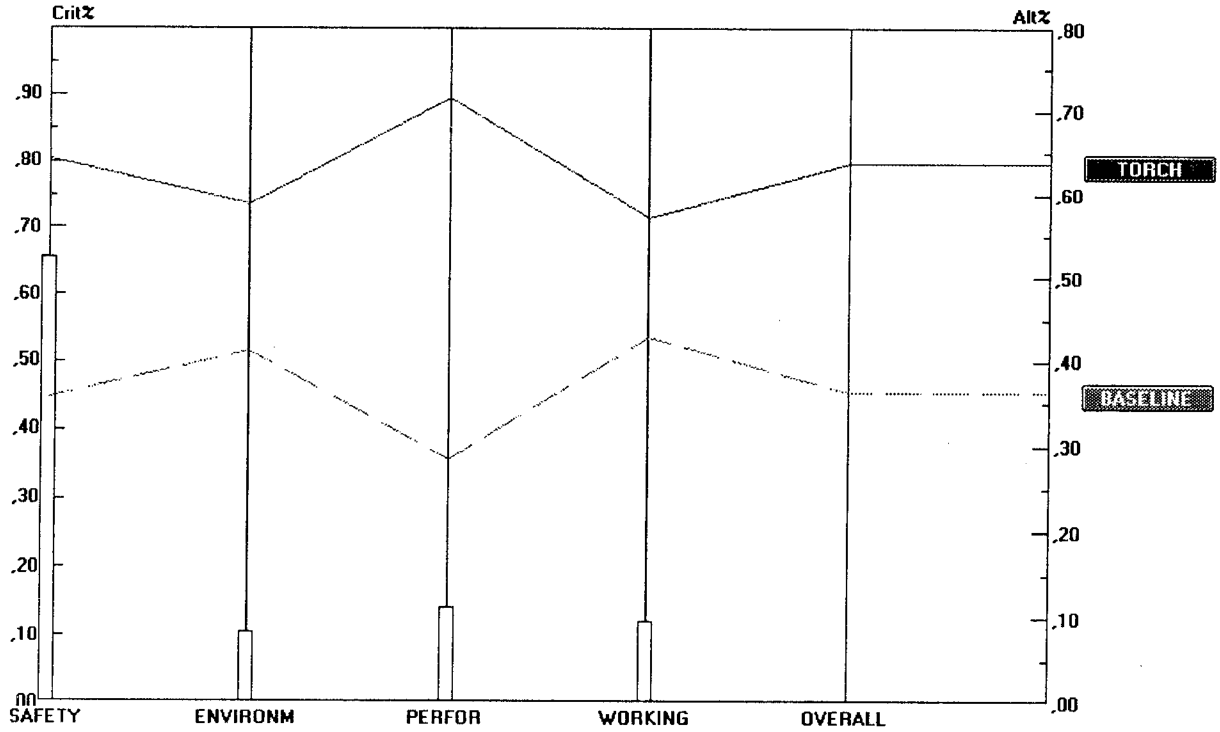


FIGURE 15 Sensitivity analysis for effectiveness (ungrouped data).

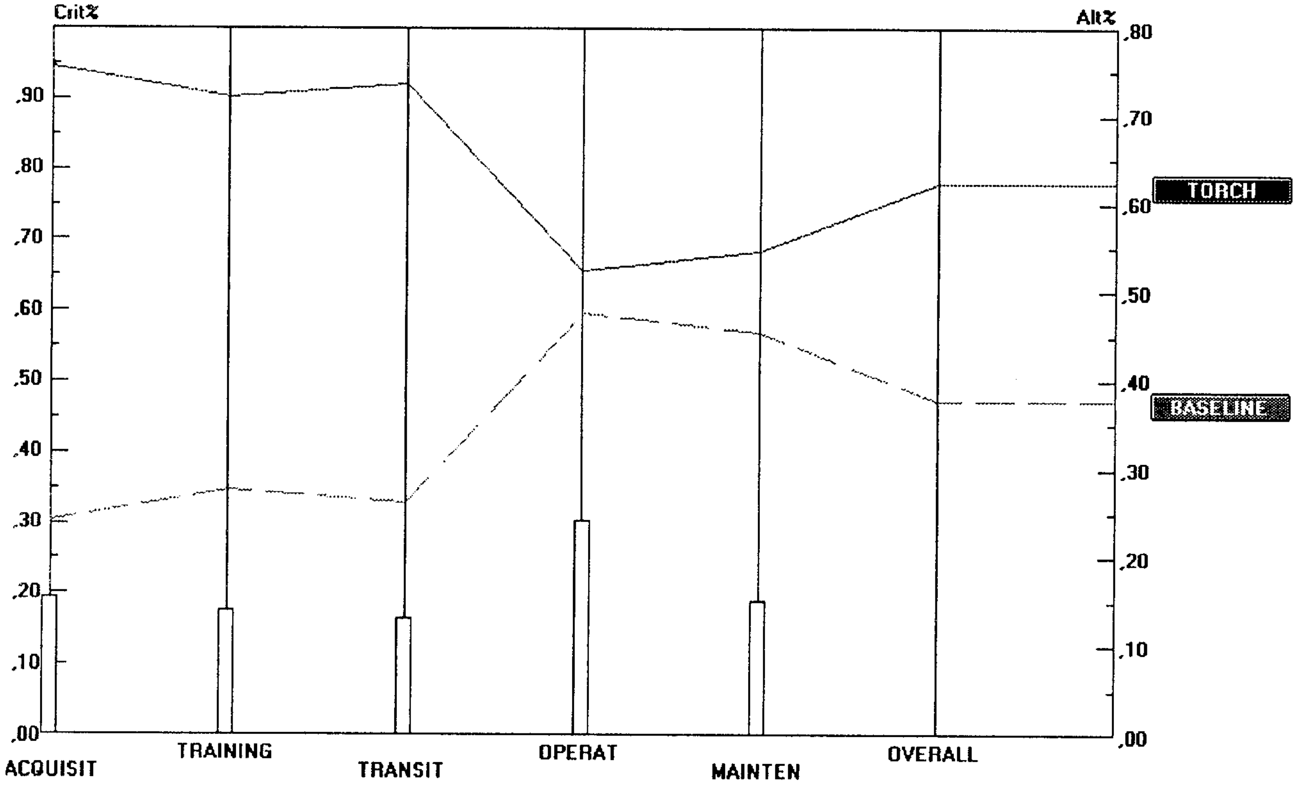


FIGURE 16 Sensitivity analysis for cost (ungrouped data).

environmental impact criterion was considered to have the least importance, 10 percent.

The inconsistency ratio for the pairwise comparisons expressing the relative importance of the various criteria measuring the effectiveness of the ATM system was found to be very low (i.e., 1 percent). This finding suggests that the opinions expressed by experts about the relative importance of the ranking criteria are valid in terms of their logical consistency.

The computation of the inconsistency ratio for all pairwise comparisons was made with the use of the Expert Choice software (*7*). The primary input needed to estimate the inconsistency ratio is the matrix of pairwise comparisons. An example of the pairwise comparison matrix corresponding to the inconsistency ratio calculated in Figure 8 is given in Table 5.

The values presented in Table 5 represent the geometric mean of the corresponding pairwise comparisons of the panel of experts.

More detailed analysis of the relative importance of the indicators expressing the four effectiveness criteria was conducted in order to identify the major determinants of the relative importance of each criterion. The results of this analysis for safety, environmental impacts, system performance, and working conditions are presented graphically in Figures 9, 10, 11, and 12, respectively. Figure 9 suggests that the major determinant of the relative importance of the safety criterion was the number of fatalities per year, followed by the number of accidents per year and the number of airport-related accidents per year. These three criteria account for about 85 percent of the safety criterion, while the remaining two (i.e., number of air misses per year and airport-related incidents per year) account for the remaining 15 percent.

Figure 10 illustrates the ranking of the relative importance of the environmental impact indicators. The indicators with the highest importance in measuring environmental impact are the maximum level of noise and the average noise level, which together account for 64 percent of the environmental impact criterion. The other two—emission and fuel consumption—account for the rest (36 percent), and they were considered of equal importance.

Figure 11 shows that the most important indicators expressing system performance were found to be the arrival/departure delay, accounting for 41 percent, and the number of aircraft movements, accounting for 22 percent. The rest of the weight is equally split among the other indicators measuring ATM system performance (i.e., en-route delay, degree of harmonization of ATM among countries of the European Union, and flexibility in modifying flight plans).

The indicator expressing the degree of harmonization of the ATM system in Europe (HARMONI) was found to be important, accounting for 10 percent of the ATM system performance determination. The values of relative importance assigned to this indicator by the expert panel are shown in Figure 17.

The in-depth analysis of the indicators expressing the working-conditions criterion, Figure 12, suggests that the most important indicator is the stress level, which accounts for one-third of the working-conditions criterion. The remaining 67 percent is split almost equally among the other three indicators—job satisfaction, workload level, and training needs for using ATM tools effectively.

The last step of the analysis of the ungrouped data was to perform sensitivity analysis to determine how robust the ranking of the two alternatives is in terms of the relative importance of the four major effectiveness criteria. The results of the sensitivity analysis are presented in Figure 15. The first result emerging from this analysis is that the TORCH system outperforms by far the BASELINE not only in terms of their overall performance (i.e., 64 percent for TORCH versus 36 percent for the BASELINE) but also in terms of each criterion independently.

One can see that the biggest difference in the rating of the two systems is attributed to the system performance (i.e., reduction of delays, higher flight plan flexibility, etc.) followed by their safety performance. The smallest difference in the rating of the two systems is expected to be in their environmental impacts and their effect on the working conditions.

The robustness of the ranking of the two systems is demonstrated by the fact that the BASELINE system performance line (dotted line) does not cross over the TORCH system performance line for any of the effectiveness criteria. This simply means that, even if the relevant importance of any criterion was changed enormously (i.e., approximately 100 percent), the ranking of the two alternatives would not be reversed.

Costs

The results of the cost analysis (see Figure 13) of the two alternative ATM systems revealed that the TORCH system is considered to have a higher cost compared with the BASELINE system. More specifically, TORCH proved to be more expensive than the BASELINE system. The pairwise comparisons provided by the experts are considered to be logically consistent because the inconsistency ratio is found to be only 1 percent.

Five indicators were used to express the cost of an ATM system—operational cost, acquisition cost, training cost, transition cost, and maintenance cost. According to Figure 14, the operational cost represents the highest portion of the system costs, followed by the acquisition and the maintenance costs (i.e., operational cost represents 30 percent of the total cost, and acquisition and maintenance costs each represent 18 percent of the total cost). Training and transition costs were found to be of equal importance (i.e., they represent 17 percent and 16 percent of the total system cost, respectively).

The sensitivity analysis performed (see Figure 16) suggests that the ranking of the alternative ATM system is not sensitive to changes in the relative importance of the cost criteria because the fluctuation curves of the alternatives do not cross over each other for any criterion.

TABLE 5 Pairwise Comparisons Matrix for the Second Level of the Hierarchy for Effectiveness Assessment

Selection of the most effective ATM system	Safety	Environment	Performance	Working Conditions
Safety	1	6.1	5.5	5.4
Environment		1	0.8	0.7
Performance			1	1.5
Working Conditions				1

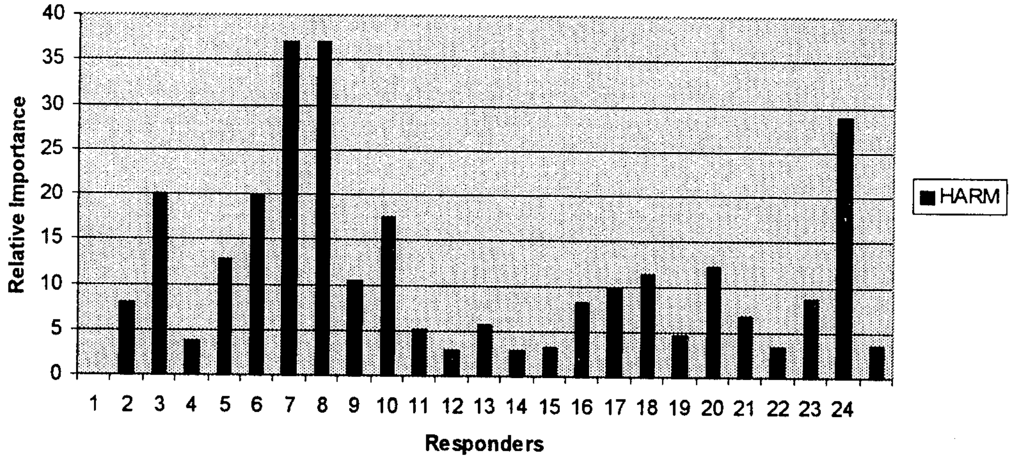


FIGURE 17 Degree of harmonization of the ATM system in Europe.

Cost-Effectiveness Ratio

Based on the analysis performed for the effectiveness and the cost of the two systems, it is now possible to form the cost-effectiveness ratio for TORCH and BASELINE. The cost-effectiveness ratio is calculated by dividing the effectiveness of each system by the corresponding cost.

Table 6 summarizes the effectiveness and cost scores assigned to the two systems as well as the corresponding cost-effectiveness ratios. Based on the results provided in Table 6, the TORCH system is more cost-effective than the BASELINE system.

Although the TORCH system has a cost-effectiveness ratio exceeding 1 and the BASELINE system has a cost-effectiveness ratio less than 1, the two ratios are very close. This small difference in the cost-effectiveness of the two systems is attributed to the high cost expected for (*a*) the development of the TORCH system, (*b*) the transition from the currently used system to TORCH, and (*c*) the training of the personnel that will use TORCH. Therefore, although there is a big difference in the expected degree of effectiveness of the two systems, there is also a big difference in the expected cost, a fact that leads to a very close cost-effectiveness ranking of the two systems. However, because the ranking of the two systems is insensitive in terms of both effectiveness and cost, the cost-effectiveness ranking of the two systems is preserved.

In conclusion, it can be stated that, based on the group of experts who participated in the survey, an investment in the development of TORCH will increase the safety, performance, and environmental friendliness of the ATM system as well as the working conditions of the air traffic controllers, while at the same time the TORCH system will be marginally cost-effective.

COST-EFFECTIVENESS ANALYSIS RESULTS FOR GROUPS OF STAKEHOLDERS

Analysis of the grouped data also led to the conclusion that TORCH is more cost-effective than the BASELINE system.

A general conclusion drawn from the analysis of the grouped data is that the cost-effectiveness ratios of the two systems are really close. Despite this fact, the TORCH system always outperforms the BASELINE system by a two-to-one margin in terms of effectiveness.

As for the relative importance of the effectiveness criteria for the various groups of stakeholders, it was found that for all groups the most important criterion is safety (i.e., expressed mainly by the number of accidents per year, the number of fatalities per year, and the number of airport-related accidents per year). The criterion ranked second by the majority of the stakeholders was system performance, which is mainly expressed by (*a*) the percentage deviation of actual arrival time as compared with the scheduled time, (*b*) the number of aircraft movements at an airport under the worst visibility conditions, and (*c*) the percentage deviation of en-route flight time as compared with schedule time. The working-conditions criterion was ranked third, with the exception of one group that ranked it second. Finally, the environmental impact criterion was ranked fourth, with the exception of one group of stakeholders that ranked it second. The emphasis among the various indicators measuring this criterion was on maximum noise level followed by fuel consumption.

As for the performance of the two systems in terms of their cost, almost all stakeholders considered that TORCH will be a more expensive system. All groups of stakeholders rated operational and maintenance costs as the cost criteria that were the most important cost contributors of an ATM system.

TABLE 6 Cost-Effectiveness Ratios of Alternative ATM Systems for the Ungrouped Data

Ungrouped Data			
ATM Systems	**Effectiveness**	**Cost**	**Cost-Effectiveness Ratio**
TORCH System	0.637	0.622	**1.02**
BASELINE System	0.363	0.378	**0.96**

CONCLUDING REMARKS

A comprehensive methodology for assessing the cost-effectiveness of a new European ATM system has been presented. The proposed methodology recognizes all the difficulties associated with the analytical measurement of costs and benefits generated by the introduction of a new ATM system. The proposed methodology was applied with the help of a panel of European ATM experts. The application results are intuitively appealing and indicate a strong convergence of the expert opinions regarding the most preferable ATM system.

ACKNOWLEDGMENTS

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Paper No. 01-3476

Modeling Airside Airport Operations Using General-Purpose, Activity-Based, Discrete-Event Simulation Tools

Julio C. Martinez, Antonio A. Trani, and Photios G. Ioannou

The application of activity-based simulation techniques to model runway operations at airports is described. The simulation tool used, STROBOSCOPE, is a discrete-event simulation system and programming language based on the three-phase activity scanning simulation paradigm. The model developed can be used as a tool to estimate runway capacity, delays, and double runway occupancy instances.

The growth of air transportation services continues to outpace the ability to improve the capacity of the National Airport and Airspace System (NAAS) in the United States. According to recent FAA statistics, the number of passengers traveling by air in the United States reached 643 million in 1998 (*1*). The number of enplanements is expected to grow to 991 million by the year 2010 (*1*). The congestion at airports continues to grow and, for the past three decades, airport authorities have looked at various ways to efficiently operate aircraft on limited infrastructure resources. Some large airports, such as the Atlanta Hartsfield International (ATL) facility, handle more than 900,000 operations per year alone (*1*).

It is recognized that the capacity of NAAS is a complex combination of the collective capacities of airports, airspace, airlines and assets, and air traffic control. However, runway capacity dictated by large headways between aircraft operating in the vicinity of airports is, without a doubt, a critical component of the overall system that limits capacity. There are numerous tools and methods to estimate airport capacity and delay. During the past two decades, simulation and modeling techniques have become more popular to study aircraft runway operations at airports with the development of several macroscopic and microscopic, fast-time simulation models. Macroscopic models such as the Airport Capacity Model (ACM), RDSIM, and DELAYS developed at the Massachusetts Institute of Technology and the Runway Capacity Model developed by the Logistics Management Institute (LMI) can be used to make policy decisions about the best runway operational practices at an airport. Microscopic models such as the Total Airport and Airspace Model (TAAM) and SIMMOD, the FAA airport and airspace simulation model, can handle detailed runway operations but at an added computational and detailed user cost. Both macroscopic and microscopic models are described in good detail by Odoni et al. (*2*) and in various sources in the literature (*3–5*).

Each of these models uses variations of the following modeling paradigms: (*a*) analytical solutions to a queuing model (case of DELAYS), (*b*) capacity approximations based on time-space approaches (Airport Capacity Model, LMI Runway Capacity Model), and (*c*) event-driven, discrete-event simulation (SIMMOD, TAAM, RDSIM). This paper describes a variation of these classical approaches to predict runway capacity and delays at airports using a general purpose, activity-based simulation system called STROBOSCOPE (*6*). STROBOSCOPE is a discrete-event simulation system and programming language based on the three-phase activity scanning simulation paradigm that has been used to model numerous construction engineering operations (*6*).

PROBLEM STATEMENT

This section describes the modeling of a runway whose details are provided here in their entirety so that the reader can re-create the modeling process and the results.

Aircraft use runways to land and depart at an airport. When aircraft arrive in the vicinity of an airport, they wait for air traffic controllers to give them permission to land. After obtaining permission to land, aircraft enter a final approach corridor of specific length (usually called common approach path), land, occupy the runway while decelerating, and finally exit to a taxiway. For aircraft departures, aircraft wait on a taxiway for instructions to enter the runway, accelerate, and take off.

The common approach path in this simulation study is 15 km in length. As aircraft traverse this common approach path, they generate wake turbulence. This turbulence must dissipate before another airplane can traverse the common approach path. The necessary dissipation time depends on the type of the aircraft that creates the turbulence and the prevailing atmospheric conditions in the vicinity of the airport, among other factors. Large airplanes create and tolerate more turbulence than smaller ones. The wake vortex phenomena, including simple models for use in airport capacity analysis, have been described in the literature (*7–10*).

In the current NAAS, air traffic controllers separate aircraft using ground-based surveillance radars. To ensure that airplanes do not encounter wake turbulence beyond the one they can tolerate, air traffic controllers comply with prescribed minimum separation standards. The minimum separation distances between successive aircraft depend on the types of the aircraft and include a "buffer" distance that acts as a safety factor. This buffer distance is prescribed as 2100 m in length but is subject to measurement errors on the part of the air traffic controller. For this reason the actual buffer is assumed to be normally distributed with a mean of 2100 m and a standard deviation of 1260 m, but truncated two standard deviations at either side of the mean (this is actually a mixed distribution).

The minimum distance between successive aircraft in the United States is shown in Table 1. When the trailing airplane is slower than the leading airplane, the minimum separation occurs when the

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TABLE 1 Minimum Distance Between Aircraft Entering the Final Approach Corridor

Following Airplane Type	Leading Airplane Type	Minimum Distance (meters)	Minimum Distance When Trailing Airplane Enters (meters)
Heavy	Heavy	6000	6000
Heavy	Medium	6000	6840
Heavy	Light	6000	8760
Medium	Heavy	9000	9000
Medium	Medium	6000	6000
Medium	Light	6000	8120
Light	Heavy	12000	12000
Light	Medium	9000	9000
Light	Light	6000	6000

airplane that follows enters the common approach path. When the trailing airplane is faster than the leading airplane, the minimum separation occurs when the leading airplane crosses the runway threshold. In addition to the minimum distance, Table 1 shows the necessary separation between aircraft when the trailing airplane enters the common approach path. In Table 1, three aircraft classifications are used: light, medium, and heavy. This classification is based on aircraft maximum gross mass. Light aircraft have a maximum takeoff mass of less than 18 635 kg. Medium-size aircraft weigh up to 116 000 kg, and heavy aircraft are those with a maximum takeoff mass greater than 116 000 kg.

Based on Table 1, an air traffic controller will not authorize a heavy plane to enter the common approach path until a light plane is at least 8760 m + Normal[2100, 1260] m into it. The length of the common approach path may allow up to three aircraft to occupy it simultaneously (e.g., if the minimum distances between them are short).

To prevent a landing aircraft from occupying the runway simultaneously with a departing aircraft, air traffic controllers do not authorize airplanes to enter the runway and take off unless the next airplane to land is at least 3200 m away from the beginning of the runway. This is typically called the arrival-departure distance. It is chosen so that a departing airplane terminates its runway occupation before the arriving aircraft touches the runway. Occasionally, if the arriving aircraft has a high approach speed (e.g., a heavy airplane) and the departing aircraft has a long runway occupation time during takeoff (e.g., a light airplane), the arrival-departure distance may allow the two planes to occupy the runway simultaneously for a few seconds. Because landing and departing operations are always in the same direction, this double occupation occurs at opposite ends of the runway and is the subject of much debate in the analysis of runway incursions.

Departing aircraft also create wake turbulence that affects other aircraft departing on the same runway. For this reason, there are standards to prescribe minimum times between successive departures to account for differences in takeoff speed (i.e., to prevent a fast plane from overtaking a slow plane) and for wake turbulence effects. These times are shown in Table 2.

The speed of landing aircraft while in the common approach path depends on the type of aircraft. The time of runway occupation is normally distributed and depends on the type of aircraft and on whether the aircraft is landing or taking off. Table 3 shows the various approach speeds and occupation times. There are dedicated computer simulation models such as REDIM to estimate these parameters with some precision (*11, 12*).

The aircraft mix for this simulation study is 33 percent heavy, 33 percent medium size, and 33 percent light. The rate at which aircraft arrive at the vicinity of the airport and queue up to take off varies with the time of day. The rates are a Poisson process described in Table 4.

The purpose of this simulation is to determine the expected average and maximum daily waiting times for arriving and departing airplanes. This information is used to determine if the airport is capable of supporting the demands shown in Table 4 with acceptable delays. If waiting times are excessive, it is necessary either to reduce the traffic at the airport or to improve the utilization of the runway. One way to improve the use of the runway (or runways) is with the deployment of better surveillance technology that enables air traffic controllers to reduce the safety buffer added to the minimum prescribed separation between aircraft. This approach is currently being pursued by the FAA with the deployment of the Center/TRACON Automation System (CTAS) developed by NASA Ames and described in the literature (*12–15*).

SIMULATION MODEL

This section describes how STROBOSCOPE can be used to model and analyze the problem to determine the expected average and maximum daily waiting times for arriving and departing airplanes.

TABLE 2 Minimum Time Between Successive Departures

Trailing Plane Type	Leading Plane Type	Minimum Time Between Successive Departures (seconds)
Heavy	Heavy	60
Heavy	Medium	90
Heavy	Light	120
Medium	Heavy	60
Medium	Medium	60
Medium	Light	90
Light	Heavy	60
Light	Medium	60
Light	Light	60

TABLE 3 Approach Speed and Runway Occupation Times

Plane Type	Approach Speed (m/sec)	Landing Runway Occupation Mean (seconds)	Landing Runway Occupation Std. Dev. (seconds)	Takeoff Runway Occupation Mean (seconds)	Takeoff Runway Occupation Std. Dev. (seconds)
Heavy	75	55	6	38	4
Medium	68	50	10	43	6
Light	52	45	10	50	6

Resources constitute the fundamental entities in STROBOSCOPE models. They represent materials, parts, machines, equipment, labor, space, permits, signals, or anything else that may be required to perform tasks. Sometimes resources represent abstract concepts that are needed to model operations realistically. The STROBOSCOPE model described in this paper uses resources to represent airplanes (*Plane*), signals (*Sequencer*), and arrival schedulers (*ArvSched*).

STROBOSCOPE resources are analogous to both the entities (transactions, clients) and facilities (resources, servers) used by simulation tools based on the process interaction paradigm. In STROBOSCOPE, however, there is no distinction between entities and facilities. Although resources are an essential part of STROBOSCOPE, their role in the development of a simulation model is passive. STROBOSCOPE models are developed from the perspective of activities and not from the perspective of the resources that move through the model's network.

Figure 1 shows the STROBOSCOPE network that is used to model the airside operations. The network shows the main logic of the model without going into details. It includes nodes of various kinds connected with links that indicate how resources flow from node to node. The nodes and links in a network must be uniquely named.

The circles with a slash in the bottom right are queues. They hold inactive resources of a specific type. The queue named *PlanesWtDept* in Figure 1, for example, holds resources of type *Plane* that are waiting to enter the runway for takeoff. The rectangles (with or without cutoffs at the top left corner) are activities. They represent tasks performed by various resources working together. The duration of each activity is determined (i.e., sampled from a distribution) at the time at which the task starts. The activity in Figure 1 named *Depart,* for example, indicates that it may engage the resources held at *PlanesWtDept, Landing,* and *NotDeparting.*

Activity instances are the actual tasks that are created and performed during simulation. Different instances of the same activity can start at various times and have different durations. They can be sequential, overlapped, or intermittent. Thus, it is possible to have zero, one, or several instances of the same activity taking place at any time during simulation. Each instance of the *FirstSegment* activity, for example, represents an airplane traversing the first part of the common approach path. There may be times during which the first part of the common approach path is empty and therefore no instances of *FirstSegment* exist. At other times two or even three airplanes can be traversing the first part of the common approach path. In these cases a separate instance of *FirstSegment* represents each airplane approaching.

STROBOSCOPE models are developed from the perspective of activities. Of particular importance are Combi activities, shown with their top left corner cut off, and which can only be preceded by queues. Combis constantly check the state of the simulation to see if the conditions necessary to create their instances exist. (These checks are performed at the discrete points during a simulation run at which events occur.) When its start-up conditions are satisfied, a Combi creates an instance of itself, removes resources from its preceding queues, and determines the duration of the instance.

The conditions necessary for a Combi to create an instance can be arbitrarily complex. In STROBOSCOPE these conditions are given by the Combi's Semaphore and by the Enough attribute of each of the links that enter the Combi. The Semaphore does not depend on the resources present in the queues that precede the Combi. In contrast, each Enough depends (primarily) on the resources present in the preceding queue. For example, the conditions necessary for *Depart* to create an instance are that an airplane is waiting to depart (the *PlanesWtDept* queue contains at least one airplane); that there are no airplanes occupying the last 3200 m (arrival-departure distance) of the common approach path or landing (the *Landing* queue is empty); and that there are no airplanes departing or that have taken off too recently (the *NotDeparting* queue contains at least one resource). In the case of the *Depart* activity, all start-up conditions depend on the existence or absence of resources in the queues that precede it and are thus specified as Enoughs for the connecting links (*PL8, SQ6, SQ7*). In cases where the start-up condition is unrelated to the queues that precede the activity, the condition can be specified with a Semaphore. Semaphores typically are used in very complex models and are not needed to model the airside operations discussed in this paper.

Semaphores and Enoughs are examples of modeling element attributes. They are expressions that are attached to the corresponding modeling element and that define the behavior of the element. Modeling element attributes do not need to be defined explicitly. STROBOSCOPE will always define one automatically if one is not

TABLE 4 Arrival and Departure Rates as Function of Time of Day

Time of day (hr)	Arrivals per Hour	Departures per Hour
12 PM - 6 AM	5.33	10
6 AM - 7:30 AM	16	32
7:30 AM - 9 AM	32	16
9 AM - 12 Noon	10.67	10.67
12 Noon - 1:30 PM	16	32
1:30 PM - 3 PM	32	16
3 PM - 6 PM	10.67	10.67
6 PM - 7:30 PM	16	32
7:30 PM - 9 PM	32	16
9 PM - 12 PM	10.67	10.67

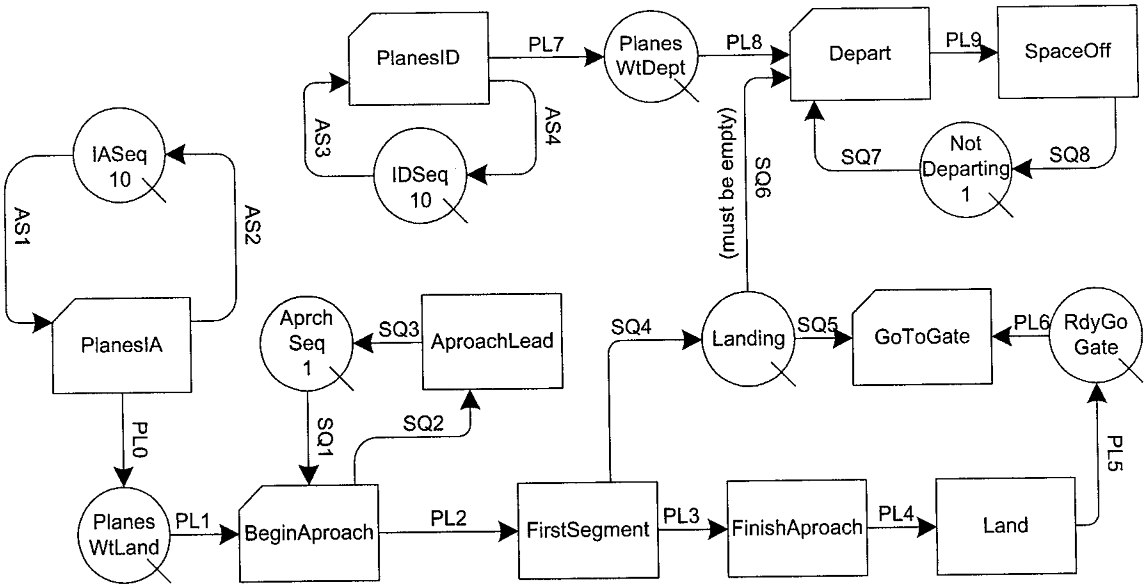

FIGURE 1 STROBOSCOPE network for airside airport operations.

provided. The Enoughs defined automatically by STROBOSCOPE return TRUE (i.e., condition met) whenever the queue at the tail of the corresponding link is not empty. As a consequence it is not necessary to specify the Enoughs for *SQ7* and *PL8*—those defined automatically by STROBOSCOPE do the job well. The Enough for *SQ6*, on the other hand, must be set to return TRUE only when the content of the *Landing* queue is zero (this is done by setting *SQ6*'s Enough to "*Landing*.CurCount= =0"). The Semaphores defined automatically by STROBOSCOPE always return TRUE, indicating that only the contents of preceding queues affect its start-up.

Once the conditions necessary for a Combi to create an instance are satisfied, the Combi removes resources from the preceding queues and determines the duration of the instance. The links that enter a Combi have several attributes that allow it to select which and how many resources they remove from the queues that precede the Combi. The automatic attributes defined by STROBOSCOPE remove one resource from each preceding queue—the first one available (i.e., queues are first in, first out by default). Each instance of *Depart*, for example, removes one resource from *NotDeparting*, one airplane from *PlanesWtDept*, and no resource from *Landing*. One resource is removed from each of *PlanesWtDept* and *NotDeparting* automatically—there is no need to explicitly define attributes for *Depart* to behave this way. In order for no resource to be removed from *Landing*, however, the *DrawAmount* attribute of link *SQ6* must be set to 0.

After an activity instance has been created and its duration determined, it is dormant until the simulation time at which the instance ends. At that time the activity instance releases the resources it held to its successor nodes and is destroyed. When an instance of *Depart* ends, for example, an instance of the *SpaceOff* Normal activity is created, and the airplane is sent to it. Sometimes activity instances generate resources before their termination in order to release resources that had not been acquired during instance creation. *PlanesID*, for example, generates one airplane before terminating its instances. This allows each terminating instance of *PlanesID* to release an airplane to *PlanesWtDept*.

Normal activities are shown as plain rectangles and cannot be preceded by queues. They create instances without the need to check conditions. They simply react to the destruction of a predecessor instance. An instance of *SpaceOff*, for example, will be created each time an instance of *Depart* ends. The instance is created with the airplane it receives.

MODELING ARRIVALS

Airplane arrivals to the system are modeled by the portion of the network composed of the *PlanesIA* Combi activity; the *IASeq* queue; and the *AS1*, *AS2*, and *PL0* links. This portion of the model generates an airplane of the appropriate type (*Light*, *Medium*, or *Heavy*) according to the rates specified in Table 4 and places them in the *PlanesWtLand* queue. Ten resources of type *ArvSchd* (arrival schedulers) are initially in *IASeq*. Each of these 10 resources represents the information in the first two columns of the corresponding row in Table 4, and each enables the creation of a separate instance of *PlanesIA*. The duration of *PlanesIA* is set such that each instance ends at the time at which an airplane of the corresponding time period arrives. Each time an instance of *PlanesIA* terminates, an airplane is generated. The type of the airplane is determined such that there is an equal probability of the plane being light, medium, or heavy. Each airplane has properties determined from its type that correspond to those specified in Table 3. In addition, each plane has a *MinLeadTime* property that specifies the minimum separation time between itself and the next plane to arrive. This value is determined by looking up in Table 3 (which is represented by a matrix in STROBOSCOPE), adding a stochastic buffer, and dividing by the approach speed. On termination of *PlanesIA*, the arrival scheduler is released to *IASeq*, where it immediately enables the creation of another instance of *PlanesIA*. Arrival schedulers are thus constantly circulating in this part of the network and constantly introducing arriving airplanes to the system.

Airplanes that wish to depart are generated independently of arrivals according to the rates specified in Table 4 and are placed in the *PlanesWtDpt* queue. This is done by means of the *PlanesID* Combi activity, the *IDSeq* queue, and the *AS3*, *AS4*, and *PL7* links in much the same way as the arrivals to the system are modeled.

MODELING APPROACH AND LANDING

The system logic that controls airplanes approaching the runway and landing is defined by the portion of the network consisting of nodes *PlanesWtLand, AprchSeq, BeginAproach, AproachLead, FirstSegment, Landing, FinishAproach, Land, RdyGoGate,* and *GoToGate*. The activity *BeginAproach* is a zero-duration dummy that marks the entry of an airplane into the common approach path. It can start whenever both the *AprchSeq* and *PlanesWtLand* queues contain at least one resource each. *AproachLead* takes place immediately after *BeginAproach* concludes, and its duration is set to the minimum lead-time of the corresponding plane. It is after this time has passed that a resource is released to *AprchSeq,* thus preventing other airplanes that may be in *PlanesWtLand* to begin approaching during that time. *AproachLead* models the minimum separations between airplanes in the common approach path.

FirstSegment also takes place immediately after *BeginAproach* concludes. It represents an airplane traversing the first 11 800 m of the common approach path. *FinishAproach* starts immediately after *FirstSegment* and represents an airplane traversing the last 3200 m of the common approach path. The common approach path is broken into two parts so that once the first part is traversed, a resource is deposited in the *Landing* queue and prevents departures from starting. The *Land* activity takes place immediately after *FinishAproach* and represents the time of runway occupation while the airplane lands. On completion of *Land,* the airplane is released to the *RdyGoGate* queue, which enables the *GoToGate* activity to start and to remove the resource that was placed in *Landing* when *FirstSegment* ended.

MODELING DEPARTURES

The logic of airplanes departing is defined by the portion of the network consisting of nodes *PlanesWtDept, NotDeparting, Landing, Depart,* and *SpaceOff.* Departures can start (*a*) when there are no airplanes in the final 3200 m of the common approach path or landing, which happens only when the content of the *Landing* queue is zero; (*b*) when there are airplanes waiting to depart, which happens when the content of the *PlanesWtDept* queue is not zero; and (*c*) when there are no other airplanes departing or that have recently taken off, which happens when the content of *NotDeparting* is not zero. *NotDeparting* starts off with one resource, which is removed every time *Depart* begins and is returned each time *SpaceOff* ends. The duration of *SpaceOff* is such that it adds to the runway occupation time the time required to meet the minimum times between successive departures specified in Table 2.

MULTIPLE RUNWAY OCCUPANCY

It is a potential safety hazard for more than one airplane to occupy the runway at the same time. If the parameters used in the model are correct, this should seldom happen, and then for only a very few seconds. For arriving airplanes this is not an issue and is taken care of by the minimum separation in the common approach path. For departing airplanes it is not an issue either because the air traffic controller will not authorize a departure when the runway is occupied. However, because air traffic controllers squeeze departures between arrivals, it is possible for an arriving airplane to touch the runway before a departing airplane has taken off. In terms of the model, this would happen when an instance of the *Land* activity starts before an instance of the *Depart* activity ends. This can be detected, and the amount of double occupancy time determined, by checking, when an airplane flows through *PL9,* if an instance of *Land* is taking place ("*Land*.CurInst>0"in STROBOSCOPE code). If it is, the time of double runway occupation is that time minus the time at which the last instance of *Land* started ("SimTime-*Land*.LastStart" in STROBOSCOPE code).

RUNWAY PERFORMANCE

With the exception of some minor details, particularly those dealing with output and its formatting, the entire STROBOSCOPE model for the airside operations has been discussed. A run of the model with 10 batch means replications, each 1 day in length, yielded the results shown in Table 5, which are taken directly from the output. The columns indicate, for each day and for both arrivals and departures, the average number of arrivals per hour, the maximum waiting time, and the average waiting time.

These results indicate that the average daily waiting time for arriving airplanes over the 10 days simulated is about 12 min and about five times longer than the average daily departure times. The maximum

TABLE 5 Airport Simulation Daily Arrival and Departure Values

	Daily Arrival Values			Daily Departure Values		
	Average Arrivals per hour	Maximum Waiting Time (min)	Average Waiting Time (min)	Average Departures per hour	Maximum Waiting Time (min)	Average Waiting Time (min)
	14.36	82.16	14.28	14.86	18.13	2.59
	13.96	58.63	9.16	14.37	14.03	1.90
	14.83	70.19	17.97	13.87	17.36	3.06
	14.23	64.04	15.96	14.73	14.22	2.09
	13.11	43.28	6.46	12.69	8.77	1.11
	14.41	35.06	7.24	13.08	14.84	3.52
	14.37	52.30	7.80	14.12	12.35	2.00
	13.91	78.05	12.38	14.37	11.68	1.77
	15.12	64.87	18.51	14.79	18.22	3.59
	13.94	50.86	11.48	14.15	13.98	2.32
Mean	14.23	59.94	12.12	14.10	14.36	2.40
Std. Dev.	0.55	14.93	4.45	0.72	3.00	0.80

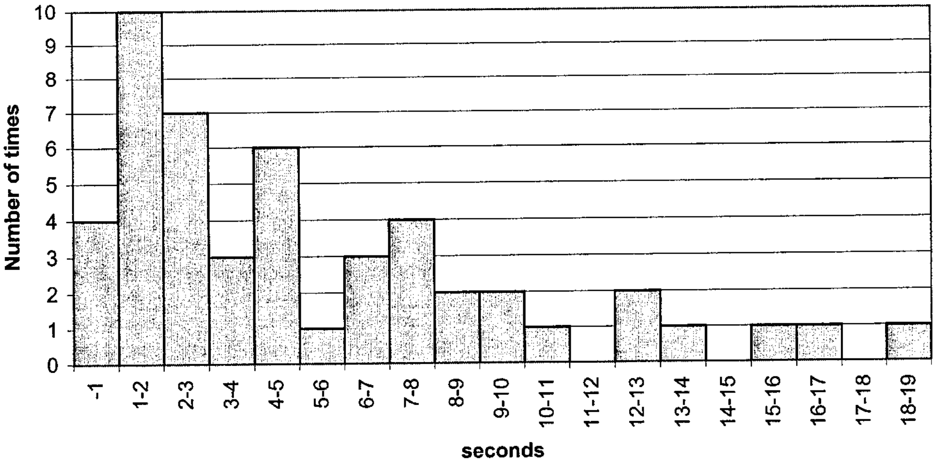

FIGURE 2 Double runway occupations in 10 days.

waiting times average about 1 h for arrivals and 14 min for departures. The model also collected statistics on double runway occupancies (over the 10 days simulated) as shown by the histogram in Figure 2.

The model results are consistent with the results obtained using analytic models such as the FAA Airport Capacity Model and stochastic queuing models (see Figures 3 and 4). Under the same aircraft mix conditions, ACM predicts a saturation capacity of 26 arrivals per hour. It should be noted, however, that both the analytic and stochastic queuing models assume steady-state conditions that seldom occur at real airports. The model presented here predicts aircraft delays under a time-varying demand function (see Table 4). Figure 3 shows graphically the behavior of arriving aircraft delays for a period of 20 operating days. Figure 4 shows the delays for arriving and departing aircraft as a function of the total number of operations. All simulations assume arrival priority.

CONCLUSION

Simulation is a very powerful and effective modeling methodology for representing and analyzing runway operations. These models traditionally have required the use of specialized simulation systems because the complexity of the logic involved made it difficult to efficiently represent them using the general-purpose simulation tools in common use, which are predominantly based on the process-interaction paradigm. Three-phase activity scanning simulation languages such as STROBOSCOPE are ideally suited to represent the complex start-up conditions for the multitude of activities that must take place concurrently in the runway operations of an airport. By shifting the focus from the question "What can the system do for a resource?" to the more democratic "What tasks can the resources perform?" it is possible to model and analyze large, complex networks of interrelated and interdependent activities with relative ease. A simulation model for runway operations such as the one presented in this paper, for example, requires only a few hours to develop and a few seconds to run. More complex airports with several runways and sophisticated operating strategies also can be developed with relative ease.

ACKNOWLEDGMENT

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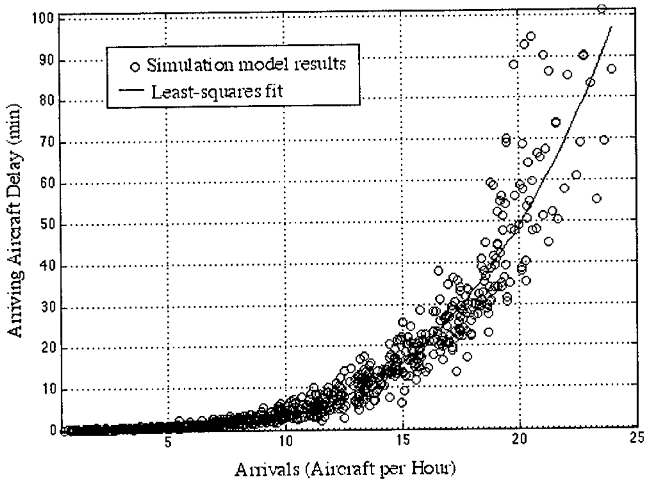

FIGURE 3 Arriving aircraft delays.

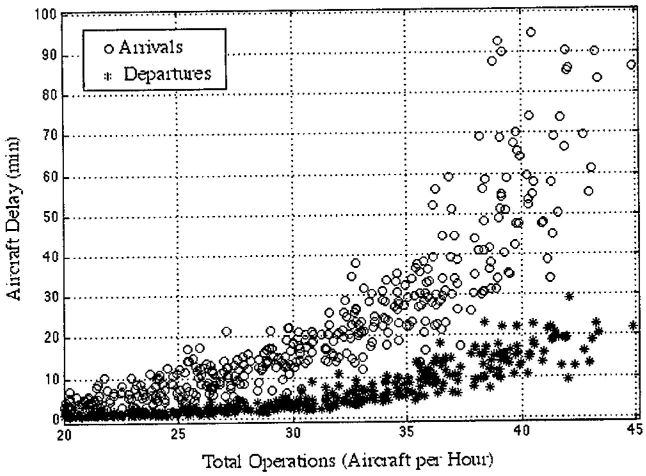

FIGURE 4 Total aircraft operations and delays.

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Paper No. 01-3270

Investigation of Information Needs of Departing Air Passengers

Debra Burdette and Mark Hickman

Specific information needs of departing air travelers for pretrip and en-route phases of trips to the airport were studied and identified. From the results, effective plans for providing supplementary information in support of groundside travel information can be developed by local, state, and national agencies. To better understand air passenger information needs, personal interviews were conducted with 216 passengers at George Bush Intercontinental Airport in Houston, Texas. One major finding from this research was that, in general, passengers are content with the types of real-time travel information that are presently available. Specifically, survey results showed that passengers currently use and prefer access to flight information including confirmed schedules, flight delays, and gate assignments. Also, most passengers prefer to receive travel information earlier in their trip (i.e., before beginning their trip), thus validating theories that suggest that if passengers are to effectively evaluate transportation options, they must have information earlier in the decision-making process. Lastly, based on the survey results, air passengers indicated they prefer to use airline employees, e-mail, telephones, and the Internet when making future travel information inquiries. In particular, business travelers were found to have a higher affinity toward e-mail and pagers, whereas younger travelers simply preferred newer technologies to receive travel information. As a result, these population categories are prime targets for information services marketing. Overall, each of these findings was similar to—and confirmed the results from—previous studies.

Implementation of the Intermodal Surface Transportation Efficiency Act in 1991 encouraged development and use of advanced technology to help manage urban transportation systems. Substantial progress has, therefore, been made in the area of intelligent transportation systems (ITS) to provide enhanced mobility, safety, and traveler convenience. Advanced traveler information systems (ATIS), a subcomponent of ITS, offer real-time traffic conditions to motorists, enabling them to make more informed decisions on travel mode, route, and time of departure. Traditionally, advanced traveler information systems provide travel times and route guidance to auto drivers, especially commuters in large urban areas (*1*). However, to address congestion on already overtaxed automobile-based transportation systems, the goal is to include information on other modes, not just highways.

In 1995, the Bureau of Transportation Statistics estimated nearly 200 million person-trips over 100 mi one-way were taken by airplane, a 186 percent increase since 1977 (*2*). As popularity of air travel continues to increase, the number of trips to and from airports will inevitably rise. Although some information needs of air travelers overlap with those of commuters, the multimodal nature of air travel makes the trip, as well as information needs, more complex. Passengers will need accurate information about all modes on a total trip basis, including the actual trip and access to and from the airport (*3*).

Little research has been conducted to determine specific information needs of departing air travelers regarding pretrip and en-route phases of trips to the airport. By addressing this issue, states, regions, and metropolitan areas could provide supplementary information in support of groundside travel, thus making advanced traveler information systems truly multimodal, capable of serving all travelers.

To understand air travelers' priorities, details on passengers' traveler information needs were gathered through personal interviews with departing passengers whose airplane trip on the survey day originated at George Bush Intercontinental Airport (IAH) in Houston, Texas. Interviews were also conducted with bus patrons on Houston METRO transit vehicles via the airport. Houston was chosen because of the amount of real-time traffic and transit information services available.

TRAVELER INFORMATION

Findings of this research were compared with two previous studies focusing on air travelers' information needs. The first, a comprehensive multimodal study of I-95 Corridor (Maine to Virginia) travelers, was conducted by Urban Engineers, Inc. This research effort included focus groups and on-site interviews at the Newark, New Jersey, and Boston, Massachusetts, international airports.

Focus group and on-site interview participants identified the following major pretrip and en-route information needs:

- Destination weather conditions,
- Flight departure and arrival times,
- Flight delays and how long a delay is anticipated,
- Destination airport information, and
- Airfare and payment method (pretrip only).

The sources air passengers would use to receive information and their willingness to pay for their use also were examined. When asked about preferred technologies, the most frequent choices were telephones and computers, specifically cellular phones, airline information numbers, the Internet, and kiosks. Although study results indicated a definite need for air travel information, participants felt it is the airlines' responsibility to provide information free of charge (*4*).

In 1993, the California Department of Transportation launched a demonstration program to evaluate computerized kiosks' effectiveness in meeting ground transportation information needs of air travelers. Four California airports furnished with 22 kiosks, along with 50 others installed at Los Angeles International Airport for a similar

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project, were used as a basis for this evaluation. Researchers interviewed general airport users, regardless of experience level in using kiosks, to identify information needs of air passengers, gather reactions to current ways airports provide information, and evaluate general awareness of the kiosks (5).

The majority of passengers said they did not have any information needs. Of those who had information needs, the most common requests were for ground transportation options and rental car information. These passengers also preferred receiving travel information from printed display boards or staffed information desks rather than an interactive video information system. General airport user awareness of the kiosks was relatively low, ranging from 16 percent to 32 percent depending on the airport surveyed (5).

Air passengers currently get their trip information from a variety of "sponsoring agencies" that collect and report real-time data. For example, highway information is collected and distributed by departments of transportation on federal, state, and local levels; up-to-the-minute transit information is obtained and reported by transit agencies; and real-time flight and airport information is collected and distributed by airlines or airports. Some sponsoring agencies believe private companies could be more effective in disseminating traveler information. By using independent information service providers (ISPs), public agencies can sell their information and end users can get customized products that better meet travelers' needs.

The following sources of pretrip and en-route information were identified:

- Internet,
- Variable message signs,
- Travel agent/airline reservation personnel,
- Commercial radio and television,
- Airport arrival/departure monitors and display boards,
- Advisory radio,
- Kiosks,
- Telephones, and
- In-vehicle navigation systems.

SURVEY DEVELOPMENT, DATA COLLECTION, AND DATA ANALYSIS

Survey Development

To investigate passengers' real-time highway, transit, and flight information needs, personal interviews were conducted with 216 passengers departing from George Bush Intercontinental Airport. The target audience included passengers departing on a flight from the airport whose airplane trip, on the date of the survey, began at Intercontinental Airport. This ensured that respondents had experience traveling on surface roadways in the Houston area. Airport passengers were divided into two categories: auto users and transit users. Transit users included those who used METRO's 112 Downtown Direct bus service to get to the airport. All other participants were classified as auto users.

Two interview questionnaires designed specifically for use at the airport and on transit vehicles served as the primary measurement tools in this investigation. The intent was to identify passenger trip-making characteristics, determine what information passengers currently use or would like to have, and if having this information had an impact on their travel behavior. These surveys also explored methods in which air passengers would like to receive information and at what point in their journey they wanted travel information. Questions were designed to supply data for a proposed set of test hypotheses.

Additional questions requested by METRO covered passengers' use, awareness, and opinion of the 112 Downtown Direct service. Due to a small transit-user sample size, results from the additional questions were omitted from this report. Copies of the auto- and transit-user interview questionnaires can be found in the author's master of science thesis (*6*).

Data Collection

Personalized, one-on-one interviews using the open-ended survey form were performed in compliance with traditional survey and interview protocols. Each interviewer was given a laminated card with lists of possible types of travel information and sources. These cards were used so that each survey participant was treated equally and to reduce the introduction of survey bias when using different interviewers.

The pilot test of the survey was conducted at Intercontinental Airport in Terminal C on November 15, 1999, to ensure that passengers accurately understood the questions and that desired information was obtained. Following the pilot test, passengers were interviewed at Intercontinental Airport's Terminal C and on METRO buses en route to the airport.

Data Analysis

The population for this investigation included all departing passengers whose flight on the date of the survey originated at IAH and left the airport from Terminal C between the hours of 6:00 a.m. and 6:00 p.m. on the Mondays and Fridays surveyed. To get a representative sample of transit users, a population for the METRO transit survey consisted of all departing air passengers who used the 112 Downtown Direct route between 6:00 a.m. and 7:00 p.m. on the Monday and Tuesday the survey was administered.

Once passenger survey data were collected, summary statistics for each survey question were calculated and are presented in the results section. Categorical data analysis techniques were then used to test the set of hypotheses found in Table 1, with the results also exhibited in the results section. Population strata for evaluation included

- Trip purpose,
- Current sources used to obtain travel information,
- Use and preference of alternative technologies,
- Familiarity with the road network surrounding the airport,
- Access and use of advanced technologies such as cell phones and pagers,
- Gender,
- Income,
- Age, and
- Frequency of travel.

Test Hypotheses

Hypotheses used to test passenger information needs theories were similar to those used in previous studies. In particular, several hypotheses appeared in the I-95 Corridor Study, including a cross tabulation of preferred information types and sources with age, accessible

TABLE 1 Proposed Test Hypotheses

Test Hypotheses	
Hypothesis #1	A higher percentage of female air travelers received some travel information compared to male air travelers.
Hypothesis #2	A higher percentage of business travelers attempt to obtain travel information compared to leisure travelers.
Hypothesis #3	A greater percentage of travelers who are less familiar with the Houston area obtained travel information compared to travelers who are familiar with the area.
Hypothesis #4	A greater proportion of non-frequent air travelers received traveler information, as compared to frequent air travelers.
Hypothesis #5	More business air travelers prefer to receive traveler information in a personalized form (i.e., e-mail and pager) compared to leisure travelers.
Hypothesis #6	More leisure air travelers prefer to receive traveler information in a public form (i.e., all sources other than e-mail and pagers) compared to business travelers.
Hypothesis #7	Air travelers who currently obtain traveler information through traditional sources prefer to obtain the proposed types of traveler information thorough alternative sources, as compared to those who did not obtain traveler information.
Hypothesis #8	Travelers who regularly use devices such as cellular phones and pagers prefer to receive traveler information through alternative sources compared to those who do not use pagers and cellular phones.
Hypothesis #9	Higher income travelers prefer to receive travel information through alternative sources compared to lower income travelers.
Hypothesis #10	A higher percentage of travelers under the age of 45 would prefer to receive travel information using an alternative source compared to travelers over 45.
Hypothesis #11	Travelers who are less familiar with the transportation network near the airport felt it was necessary to change their travel decisions based on the information they receive less frequently than those traveler who are familiar with the area.

sources, information users, and income classifications (*4*). It was also suggested in the I-95 Corridor Study, the California Kiosk Demonstration Study, and other information needs studies that gender, trip purpose, frequency of travel, and familiarity with the transportation network have an effect on traveler information needs and information source choices (*4, 5*). These sources formed the basis for the 11 test hypotheses, which were analyzed using both the auto- and transit-user survey data.

Hypothesis Testing

Previously discussed hypotheses were tested using the statistical test for comparing two binomial proportions. Several assumptions were considered, the first being that sample sizes were fixed. Because the hypothesis sample sizes were extracted from the entire sample of departing air travelers, this assumption was not upheld. However, for analysis purposes, the sample sizes were conditioned, and the analysis was based solely on the number of respondents obtained in the study. It was also assumed that survey responses were independent of one another. This assumption was supported because interviews were conducted on an individual basis, and surveyors had no control over inadvertent biasing of potential respondents who may have overheard previous responses given by other participants.

Formulation of Conclusions and Recommendations

Based on results of hypothesis tests and frequency distributions of current and future information needs of passengers, conclusions and recommendations for design and implementation of an advanced traveler information system are made. Specifically, recommendations include types of information air travelers need to make informed travel decisions, how information should be presented, and potential markets for disseminating specific services. Recommendations for future research in this area are also addressed.

STUDY RESULTS

Results from interview data analysis and statistical testing of 11 hypotheses are presented in the following sections. All results and conclusions are presented assuming that information gathered from air passengers was given truthfully to the best of their knowledge.

On-Site Survey Results

Personal interviews of departing air passengers at George Bush Intercontinental Airport and on Houston METRO's transit vehicles provided valuable insight on information needs of these passengers. Table 2 summarizes data collection efforts for each day of surveying and subsequent paragraphs include an overview of the survey findings. Overall, six attempts at on-site surveying of air travelers yielded 216 responses by departing passengers, approximately a 33 percent response rate. In total, 208 of the 216 passengers surveyed were classified as auto users and interviewed on 4 different days, while 8 were transit users and interviewed on 2 days, due to time constraints.

Passenger Awareness of Information Sources

Passengers' awareness is important when considering use of travel information and use of sources to obtain information. If passengers

TABLE 2 Data Collection Effort for IAH and METRO's Downtown Direct Bus Service

Date of Survey	Not Departing on a Flight		Not Originating in Houston		Declined to Participate		Successful Responses		Total Interview Attempts
	Number	%	Number	%	Number	%	Number	%	
11/15/99	3	6.4	32	68.1	2	4.2	10	21.3	47
11/19/99	2	2.6	28	36.8	11	14.5	35	46.1	76
11/22/99	5	3.1	86	52.4	9	5.5	64	39.0	164
12/3/99	16	5.1	174	55.2	25	7.9	100	31.8	315
12/20/99	16	76.2	0	0.0	1	4.8	4	19.0	21
1/11/00	26	86.7	0	0.0	1	3.3	3	10.0	30
Totals	68	10.4	320	49.0	49	7.5	216	33.1	653

do not know information can be obtained through a certain medium, they certainly will not use that source. Overall, 140 of 216 (65 percent) passengers were aware of all the sources presented within the survey. The remaining 35 percent of survey participants indicated they were unaware or did not know of the capabilities of at least one of the proposed sources.

Survey participants were least aware of kiosks, pagers, and in-vehicle navigation systems. In contrast, all survey participants were aware of and familiar with the capabilities of arrival/departure monitors, travel agents, and airline employees. Of the 35 percent of passengers who stated that they were unaware of at least one source, 51 percent followed up that they would consider using at least one of the sources in the future, indicating that passengers surveyed are willing to try new travel information sources.

Types of Travel Information

When designing a traveler information system, it is imperative that designers include types of information passengers feel are important in making decisions, especially considering that relevance, accuracy, and availability of travel information could affect travel choices. How often a type of information is obtained is one good indicator of the importance of that information. Additional information needs travelers may have for future trips should also be considered when implementing an areawide travel information system. Figure 1 shows percentages of current requests for information as well as the percent of passengers who stated they preferred a specific type of travel information for future trips.

Per the survey, the most sought-after types of travel information were flight gate assignments, confirmed schedules, and flight delays. The least obtained types of travel information were transit information such as transit delays, fares, and travel times. These findings are consistent with those from the I-95 Corridor Study.

Surprisingly, 20 percent of all passengers interviewed stated that they did not receive any travel information for their trip that day, and 41 percent said they did not obtain their gate assignment. It seems possible that the transit users had not received any information concerning gate assignments because they had not yet reached the airport, but

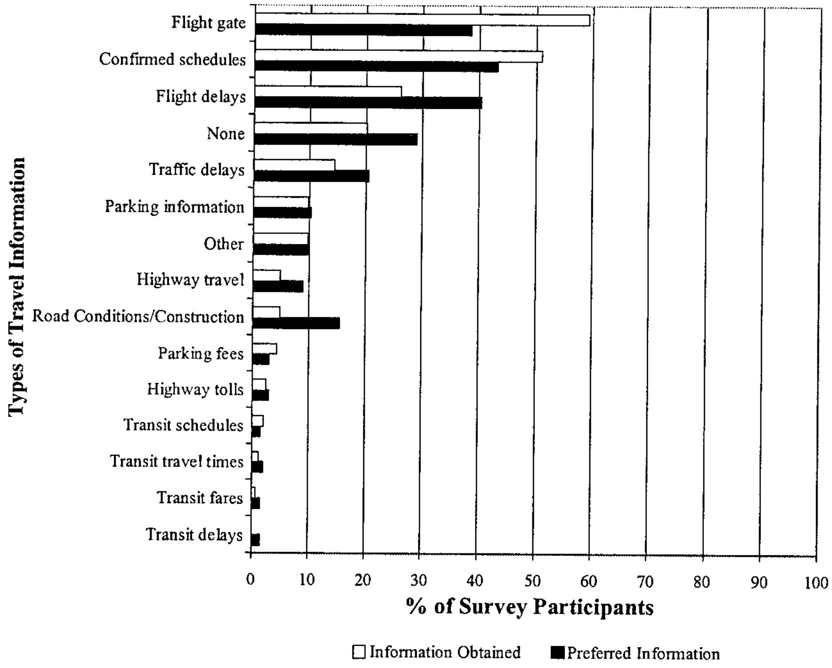


FIGURE 1 Travel information obtained and preferred by air travelers. (Passengers could choose more than one answer; a response of "None" may not represent passengers' actual feelings or behavior.)

those 80 auto users who were sitting in their departure gate area had to locate their assigned gate somehow.

Similar to the previous results, flight confirmations, flight delays, and gate assignments were the top three preferred types of information for future travel, whereas transit delays, fares, and travel times were among the least requested. It appears that the air travelers interviewed would prefer to get information on traffic conditions such as traffic delays, road conditions, construction, and highway travel times; however, they are currently not receiving these kinds of information.

The number of passengers who stated they did not want flight gate assignments in the future was puzzling. Like the passengers who stated they currently did not receive gate assignments, how would they find their planes? Additionally, the 9 percent increase in the number of passengers responding they would not use any information in planning future trips was surprising. One possible reason for the increases is passengers do not value the information they are currently receiving and do not find it beneficial to spend time looking up information for future trips. Another potential cause for the increase is the error associated with using stated preference techniques when surveying. In particular, passengers may have trouble deciding what information they would like to have or use for future trips, and therefore respond they would not use any information. A final reason for the rise in the number of passengers not requesting information is they misinterpreted the question, thinking that if they currently obtained information, it would automatically be counted toward future information needs also. Possibly passengers thought that "none" meant no new information, because 80 percent of the respondents who preferred not to have any information in the future had previously stated that they obtained some type of travel information. It is possible these concerns could have been addressed during the passenger interviews by questioning passengers on their responses, but interviewers were instructed to remain unbiased and refrain from leading passengers to give responses. Although this study obtained results similar to those of the I-95 Corridor Study, care should be exercised when interpreting the types of information results.

Travel Information Sources

The delivery method of travel information is as important as the type of information given. If information is difficult to locate or is provided via an inaccessible source, travelers are unlikely to use it. Figure 2 illustrates participants' use of and preference for different sources available to obtain information.

Survey participants used several sources to obtain their current travel information, using in order: airline employees, the telephone, and airport arrival/departure monitors. As anticipated, the less frequently used sources are among those new to the market, including kiosks, advisory radio, in-vehicle navigation systems, cellular telephones, e-mail, and pagers, each of which was used by less than 1 percent of survey participants.

Passengers' preferred sources for getting travel information are somewhat different from those they used in obtaining their current information. For future travel, passengers still would like to use the top two sources currently used; however, results showed an increased interest in receiving information via the Internet, pagers, e-mail, and cellular telephones. Additional sources identified in the other category included static signing, hotel personnel, newspapers, and rental car agents.

The currently used and preferred information source results are also similar to those found in previous investigations, particularly the sources that were found to be preferred when making future trips.

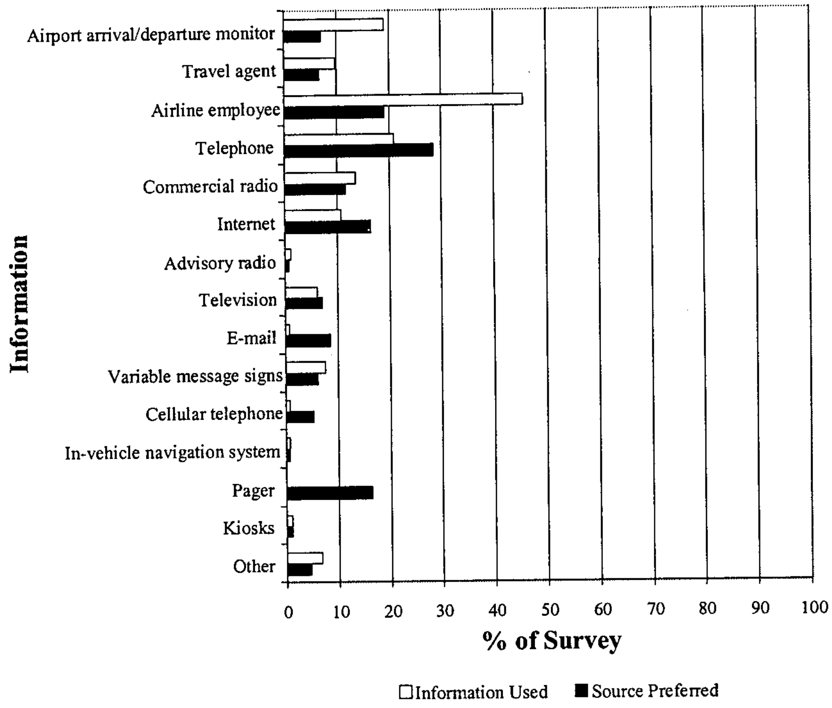


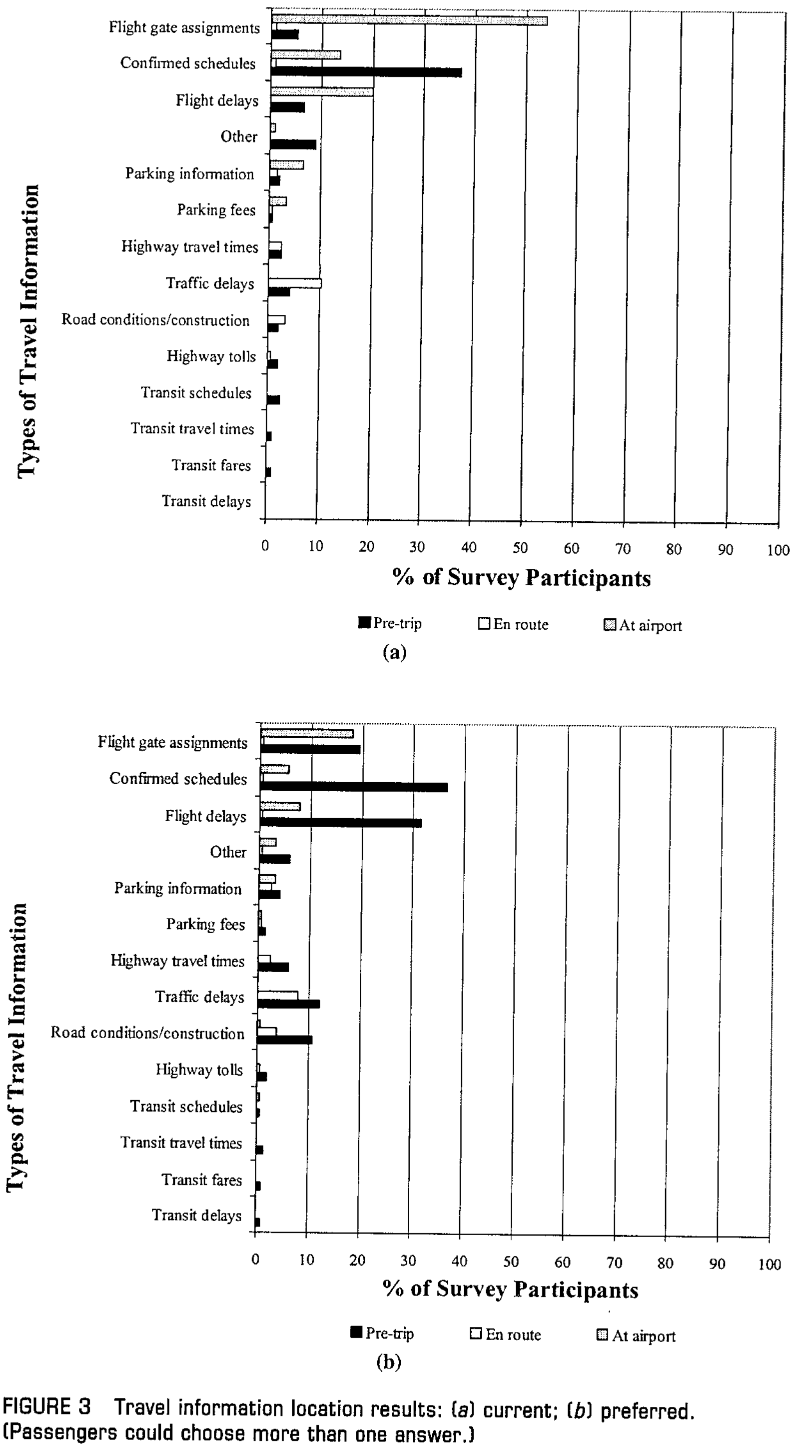
FIGURE 2 Sources used and preferred by passengers in obtaining travel information. (Passengers could choose more than one answer.)

Based on results from the I-95 Corridor Study, the telephone and computer were identified as the top two preferences to receive travel information, whereas staffed information areas were a top selection in the California Kiosk Study.

Location to Receive Travel Information

The time that travelers receive information pertaining to their trip is critical in making informed decisions. Information obtained too early could be inaccurate by the time it needs to be used and is therefore not valuable. Likewise, information received too late can also have little value to travelers because they most likely already have made travel decisions. A breakdown of when passengers received travel information for their current trip and when they prefer to obtain travel information for future trips is illustrated in Figure 3.

Clearly, passengers received the majority of their flight information when they got to the airport. Gate assignments were obtained at the airport by more than 50 percent of passengers, and nearly 20 percent of respondents getting flight-delay information received it once they



(a)

(b)

FIGURE 3 Travel information location results: (*a*) current; (*b*) preferred. (Passengers could choose more than one answer.)

reached the airport. In contrast, approximately 37 percent of passengers confirmed their schedule before making their trip, and if passengers obtained highway traffic information such as road conditions, traffic delays, or highway travel times, they typically received it pretrip or en route.

Survey participants' preferred time or location to receive travel information was drastically different from their current practices. According to the results, if passengers are to receive travel information in the future, they would prefer to have it before making their trip to the airport, no matter what type of information is obtained. The largest changes were seen from passengers who were currently getting their gate assignments and flight delay information at the airport. Other changes were seen in the percent of passengers who prefer to receive highway information pretrip as opposed to en route, as provided currently.

Changes in Travel Plans Based on Travel Information

Passengers were also asked if they felt it was necessary to change their travel plans based on the information they received. This question was intended to provide insight on passengers' use of information in making travel decisions. Only 19 of 216 passengers (9 percent) altered their trip. The most popular modifications were changes to their flight, including rebooking a canceled flight or scheduling an earlier flight, with 74 percent of these 19 passengers reporting this change.

These results do not mean that only 9 percent of the passengers used the information in making travel decisions because passengers could have checked their flight information or highway conditions and found no delays, thus proceeding on with their schedule. Those passengers still used the travel information they obtained, even though they did not feel it was necessary to change their travel plans. Because the number of passengers who were faced with situations that caused them to reevaluate their travel plans is unclear, no hard conclusions about the passengers' use of travel information can be formed.

Characteristics of the Survey Sample

The last series of questions on the surveys addressed the demographic characteristics of the traveling population. The findings from the combined transit- and auto-user surveys are presented in Table 3. It should be noted that because a breakdown of the characteristics of the entire population of air travelers at George Bush Intercontinental Airport was not available, it is not certain that the data gathered through this survey are truly representative of the population. However, the survey was administered randomly to airline passengers throughout the terminal and thus is most likely valid.

The randomly selected sample passengers revealed predictable as well as unexpected characteristics. The survey sample included 49 percent business travelers, 46 percent leisure travelers, and 5 percent other travelers, which included a higher proportion of leisure travelers than originally anticipated. The personal automobile was the preferred mode to access the airport, with 68 percent of respondents driving themselves or being dropped off at the airport. There was nearly an even distribution of frequent and nonfrequent fliers, income categories, and male and female passengers. As expected, the majority of nontransfer departing passengers were residents of Texas, and most of the Texans were from the Houston area. Because of the high number of residents in the sample, it was surprising that 43 percent of the participants were classified as somewhat or not familiar with the area around the airport, especially the transportation network. A large majority of the sample passengers had access to computing and wireless technologies and, as anticipated, used them frequently when available. Finally, the highest number of passengers surveyed fell into the age groups that included the working population.

Additional Comments from Survey Participants

As part of the passenger interview, participants were given the opportunity to provide comments about their information needs as an air traveler. The following paragraphs include a discussion and examples of some of the comments, particularly those pertaining to travel information.

Passengers' comments were divided between three categories: positive remarks, suggestions or changes needed to improve the system, and general sentiments toward travel and travel information. Several passengers indicated they were very satisfied with the information that they were currently getting and offered compliments on the airport signing available. These comments backed the preferred information results, which showed that most of the information passengers would like to have is currently available. Other passengers applauded the Internet as a travel information source, with one stating "There is a lot of information on the Internet" and another claiming "[He] has used the Internet in the past and liked it as a source."

Other comments and suggestions to improve traveler information systems included the following:

- Provide accurate and reliable information,
- Bundle information to ease search efforts,
- Offer confirmation options,
- Give information in a timely fashion,
- Include summaries of road construction in local newspapers, and
- Increase the range of advisory radio entering the airport so that information can be accessed earlier.

Finally, passengers even shared their opinions on traveling in Houston and their lack of value of travel information. Several said they were familiar with the area and made the trip so often they did not feel the need to use travel information. Others said they arrived early so they would not need any information. Lastly, one individual simply responded, "[You] cannot control travel or traffic, [you] just have to roll with the flow."

Hypotheses Test Results

Several hypotheses were proposed to test the influence of passenger demographics and characteristics on whether or not travel information is being obtained, if passengers have a preference for specific information sources, and if the information obtained is used in deciding to modify travel plans. A summary of the findings from the test of 11 hypotheses using the two sample methods is found in Table 4.

In total, only 3 of 11 hypotheses were accepted. Based on the results, it was determined that

- Passengers' frequency of travel does affect whether or not travelers attempt to obtain travel information (for air travelers in Houston, the fewer times they travel, the more likely they are to obtain travel information);

TABLE 3 Survey Sample Demographic Results

Category	Number of Responses	Percentage
Residency:		
City of Houston	89	41%
Houston Primary Metropolitan Statistical Area	124	57%
Texas	148	69%
Visitors	92	43%
Non-frequent fliers (traveled 4 or less times by air)	119	55%
Frequent fliers (traveled more than 4 times by air)	97	45%
Trip purpose:		
Business	107	50%
Pleasure	99	46%
Other	10	5%
Mode used:		
Drove self	101	47%
Dropped off	45	21%
Rental Car	29	13%
Taxi	15	7%
Courtesy vehicle	9	4%
Limo (car service)	4	2%
Bus	8	4%
Door-to-door van	4	2%
Other	1	0%
Familiarity:		
Familiar with Houston	123	57%
Somewhat familiar with Houston	69	32%
Unfamiliar with Houston	24	11%
Income:		
<$50,000	37	17%
$50,001 to $75,000	40	19%
$75,001 to $100,00	37	17%
$100,001 to $125,000	36	17%
>$125,00	42	19%
Declined to respond	24	11%
Age:		
<24	13	6%
25 to 34	39	18%
35 to 44	53	25%
45 to 54	59	27%
55 to 64	36	17%
>65	16	7%
Gender:		
Male	93	43%
Female	98	45%

- Business travelers prefer to receive travel information in personalized forms such as e-mail and pagers; and
- Younger travelers (under 45 years old) prefer receiving travel information using new or alternative technologies.

The hypotheses test results are comparable to those from previous studies. In particular, it was found in the I-95 Corridor Study that a higher percentage of respondents under 45 years old preferred receiving their air trip information via the computer compared with respondents more than 45 years old. On the other hand, some of the hypotheses test results did not back up the findings from previous studies. For instance, this study found in Hypothesis 3 that passengers less familiar with the transportation network do not necessarily attempt to obtain more travel information, whereas in the California Kiosk Demonstration Study it was suggested that they do. Likewise, the California Kiosk Demonstration Study finding that higher frequency of travel does not lead to obtaining less travel information was not supported by this study's results. Finally, the finding from the I-95 Corridor Study that low-income travelers prefer to use the television as an information source was not backed up by the results from this study.

Potential reasons for these discrepancies include the minor deviations from the exact comparisons of information sources and passenger types. For example, the California Kiosk Demonstration Study included all passenger types, whereas this study used only responses from departing passengers. Additionally, in the I-95 Corridor Study, the influence of income on passengers' preference of television as an information source was evaluated based only on the television, whereas this study included an evaluation of all traditional sources, one of which was television.

TABLE 4 Hypothesis Test Results

Test Hypotheses		Conclusion
Hypothesis #1:	A higher percentage of female air travelers received some travel information compared to male air travelers.	Reject
Hypothesis #2:	A higher percentage of business travelers attempt to obtain travel information compared to leisure travelers.	Reject
Hypothesis #3:	A greater percentage of travelers who are less familiar with the Houston area obtained travel information compared to travelers who are familiar with the area.	Reject
Hypothesis #4:	A greater proportion of non-frequent air travelers received traveler information, as compared to frequent air travelers.	Accept
Hypothesis #5:	More business air travelers prefer to receive traveler information in a personalized form (i.e., e-mail and pager) compared to leisure travelers.	Accept
Hypothesis #6:	More leisure air travelers prefer to receive traveler information in a public form (i.e., all sources other than e-mail and pagers) compared to business travelers.	Reject
Hypothesis #7:	Air travelers who currently obtain traveler information through traditional sources prefer to obtain the proposed types of traveler information thorough alternative sources, as compared to those who did not obtain traveler information.	Reject
Hypothesis #8:	Travelers who regularly use devices such as cellular phones and pagers prefer to receive traveler information through alternative sources compared to those who do not use pagers and cellular phones.	Reject
Hypothesis #9:	Higher income travelers prefer to receive travel information through alternative sources compared to lower income travelers.	Reject
Hypothesis #10:	A higher percentage of travelers under the age of 45 would prefer to receive travel information using an alternative source compared to travelers over 45.	Accept
Hypothesis #11:	Travelers who are less familiar with the transportation network near the airport felt it was necessary to change their travel decisions based on the information they receive less frequently than those traveler who are familiar with the area.	Reject

CONCLUSIONS AND RECOMMENDATIONS

General conclusions based on research findings are presented in this section. Recommendations for application and future research are also addressed.

Conclusions

In total, 216 on-site passenger interviews were conducted at the George Bush Intercontinental Airport and on Houston METRO transit vehicles. This random passenger sample represented a nearly even response rate from a variety of traveler characteristic categories such as income, age, residency, gender, trip purpose, travel frequency, and familiarity with the Houston area.

Air Traveler Information Needs

A main objective of this research was to determine what information passengers need, how they want to receive it, and at what point in their trip it would be most useful. A secondary objective was to assess whether the current system meets passenger needs and what changes are necessary to make it more effective.

Based on survey results, 76 percent of air passengers currently receive and 71 percent prefer to receive some type of travel information for both current and future trips, respectively. Information concerning passengers' flights, including gate assignments, confirmed schedules, and flight delays, were the most highly desired types of information for both current and future trips.

Comparing these results with air passengers interviewed during the I-95 Corridor Study clearly showed that both groups had similar feelings about critical pretrip and en-route information. Therefore, offering information on the flight portion of long-distance trips should become a high priority of any advanced travel information system. Results also indicated that information currently collected and distributed to passengers is perceived as valuable and should continue to be collected.

As for information sources, passengers preferred receiving travel information from other sources in addition to those they are currently using. For future travel information, passengers said they would prefer to use telephones, airline employees, the Internet, or e-mail. In particular, the Internet appears to be a much more popular information source for future trips and garnered a 19 percent increase in interest. E-mail was preferred by 23 percent of passengers, representing an increase of 23 percent. These changes were anticipated due to the increased number of people connected to the Internet and e-mail.

Again, these results are similar to those confirmed in the I-95 Corridor Study, which named telephones and computers as the top two information sources. Therefore, based on these findings and assuming passengers use these sources, new traveler information systems should plan to accommodate increased usage of these technologies.

Passengers' preferred time/location for receiving travel information is quite different from current patterns. Table 5 includes a breakdown of the currently used and preferred time/location to receive travel information for the top information requests.

Survey participants received the majority of their information at the airport or before going to the airport, whereas the least used location was en route. Table 5 shows, however, that air passengers prefer having travel information before leaving for the airport.

Based on these data, a successful advanced traveler information system should provide air travelers with information before the beginning of their trips. These results do, however, pose one potential problem for traveler information system designers and administrators.

TABLE 5 Summary of Preferred Locations to Receive Travel Information Results

Information Type and Location	Percent Currently Obtained	Percent Preferred
Flight Gate Assignments		
Pre-trip	5	20
En route	1	0
At airport	54	18
Confirmed Schedules		
Pre-trip	37	37
En route	1	0
At airport	13	6
Flight Delays		
Pre-trip	6	31
En route	0	0
At airport	20	8
Highway Travel Times		
Pre-trip	2	6
En route	2	2
At airport	0	0
Traffic Delays		
Pre-trip	4	12
En route	10	8
At airport	0	0
Road Conditions/Construction		
Pre-trip	2	11
En route	3	4
At airport	0	0

Passengers obtaining travel information before departing for the airport could leave with inaccurate flight information because, for example, gate changes and flight delays can occur at any time.

Passenger Use of Travel Information

One goal of an advanced traveler information system is for passengers to put information to use in making informed travel decisions. Most passengers did not feel it necessary to change travel decisions after obtaining specific travel information, possibly validating existing plans. In fact, 91 percent of the passengers surveyed did not change travel plans at all. However, just because a passenger did not alter his/her schedule, change access modes, or do something different, it does not mean the information was not valuable. Of the 19 passengers who indicated they changed travel plans, most cited a modification in departure time or flight schedule.

Recommendations

It is, therefore, highly recommended that any advanced traveler information system targeting air travelers should concentrate on the following aspects of the flight portion of any trip:

- Flight gate assignments,
- Confirmed schedules, and
- Flight delays.

This information should be offered via telephone and computer technology, specifically telephone information numbers, e-mail, and the Internet. Furthermore, it should be made available to passengers before they begin their trips to the airport, focusing particular attention on accuracy.

Marketing strategy should target three passenger segments as identified in the hypotheses tests:

- Nonfrequent fliers for any travel information service,
- Younger travelers (under 45 years old) for new or alternate technologies, and
- Business travelers for e-mail and paging services.

In summary, the following three components of a travel information system should be monitored for emerging patterns.

- As e-mail, paging, and in-vehicle navigation services become more widespread, future studies evaluating changes in passenger preferences in information sourcing should be continued.
- Accurately tracking how passengers use information in making travel decisions will be crucial to customer service.
- Passenger willingness to pay for travel information and the potential for profit should be determined.

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