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Contents

Foreword

Eight of the nine papers in this volume focus on various aspects of modern airports or airport systems, and their associated passenger, cargo, and aircraft activity. The remaining paper, Raphael and Starry's *The Future of Business Air Travel*, examines factors that may portend changes in the traditional pattern and frequency of business air travel.

Hansen and Weidner's paper, *Multiple Airport Systems in the United States: Current Status and Future Prospects*, reviews and assesses the prospects for new Multiple Airport Systems (MASs) in the United States and concludes that the U. S. air transport system has reached a point in which MASs could become a competitive industry in many regions.

Hawaii's major and secondary airports are the subject of Kawad and Prevedouros' paper, *Forecasting Air Travel Arrivals: Model Development and Application at the Honolulu International Airport*, in which the authors develop a short-to-medium-term econometric model system for forecasting air traffic arrivals.

In their paper on *Flight Sequencing in Airport Hub Operations*, Chang and Schonfeld propose an efficient heuristic method to minimize the total costs of passenger transfer, aircraft ground time, and gate utilization.

Parizi and Braaksma's paper, *An Optimum Resource Utilization Plan for Airport Passenger Terminal Buildings*, describes an operational planning tool that, with additional research, has the potential to be used in operating Passenger Facility Buildings (PFBs) at their minimum over- and under-supply cost.

The topic of pedestrian conveyor systems is analyzed in a paper by Young (*Analysis of Moving Walkway Use in Airport Terminal Corridors*). Young compares these systems with other primary air terminal modes and speculates how altering certain characteristics could increase the conveyer systems' overall utility.

Gu, Trani, and Zhong, in *Characterization of Gate Location on Aircraft Runway Landing Roll Prediction and Airport Ground Networks Navigation*, present and aircraft landing simulation and prediction model using simple kinematics, coupled with individual parameters to describe the landing process. The model could help solve ground network traffic congestion problems and improve safety.

Kiesling and Hansen note, in *Economic Characteristics of Multiple Vehicle Delivery*, that, compared with the body of literature on passenger carrier operations, there is a gap in addressing the economics of air freight transportation. Their paper helps fill this gap by addressing the economic structure of ground-side freight distribution for air express carriers.

Ricard's *Challenges in Developing an Airport Employee Commute Program: Logan International Airport* characterizes the commuting patterns of airport employees and describes available alternatives. The paper reviews the effectiveness of these alternatives, and summarizes past and future initiatives to alter current patterns.

The Future of Business Air Travel

DAVID E. RAPHAEL AND CLAIRE STARRY

Recent data indicate that business travel is slowing, and most business travelers are aggressively pursuing travel management policies that include limits on travel and negotiations with airlines for lower fares. Some analysts find that business air travel may be further adversely affected from the proliferation of communications technologies, including teleconferencing. Four findings are discussed: Statistically significant changes in the relationship of business air travel to gross domestic product (GDP) occurred in the late 1980s; recovery of business travel is likely to be less robust compared with previous business cycles. Econometric analysis of business and total passenger enplanements in the U.S. domestic air system indicate that a significant decline in the elasticity of demand with respect to GDP occurred in the late 1980s and early 1990s. About 40 industrial sectors account for 80 percent of business air travel. Median job and output growth for many of these sectors are below the national average. Many companies now turn to travel managers or travel service organizations and third-party firms to manage travel. Business air travelers are no longer willing to pay substantially higher air fares than personal travelers pay and have the skills to counter the airlines' yield management programs. Most industries are familiar with telecommunications technologies and anecdotal evidence indicates many companies are currently substituting teleconferences for travel, at least for intracompany meetings. Future advances in telecommunications and electronic communications offer additional convenient and less expensive alternatives to air travel.

During the 1970s and 1980s, business travel growth was an important component of airline industry profitability and performance. Business travel was the mainstay of the industry, providing sufficient yields to more than cover costs and enabling airlines to offer substantial discounts to personal travelers. Recent data indicate that business travel may no longer be growing, and more business travelers are taking advantage of discount fares. For example, in 1981, discount revenue passenger miles (RPMs) accounted for 70 percent of the total; by 1991, this percentage had risen to over 95 percent (*1*). Several reasons for the change in business travel have been suggested, including:

- Teleconferencing is beginning to take off. One expert predicts that telecommunications will substitute for 25 percent of business travel by 2010 (*2*). Another survey indicates a small percentage of business air travel has already been diverted to telecommunications (*3*).
- Businesses recognize that air travel costs are substantial and take steps to control these costs through use of travel management policies. Many companies are imposing policies that lower fares and impose travel restrictions.
- Corporate downsizing, especially middle managers, likely will result in fewer business travelers.

D. E. Raphael, Marcar Management Institute, 4007 Marsten Avenue, Belmont, Calif. 94002. C. Starry, TDS Economics, 1040 Noel Drive, Suite 202, Menlo Park, Calif. 94025.

To help understand the extent to which the above and other factors are influencing business travel, this study attempts to answer the following questions:

1. Has there been a downward shift in the elasticity of demand for air travel with respect to gross domestic product?
2. Which industrial sectors are the major purchasers of business air travel, and what is likely to be happening to their growth and employment profile over the next several years?
3. Are travel management policies changing corporate air travel?
4. How will teleconferencing and other communications technologies affect business travel?

This report is limited to evaluating U.S. *domestic* passenger enplanements, and relies heavily on secondary data from the U.S. Department of Transportation, Federal Aviation Administration (FAA) (*4*), U.S. Department of Commerce, Bureau of Economic Analysis (BEA) (*5*), and the U.S. Department of Labor, Bureau of Labor Statistics (BLS) (*6*).

THE ELASTICITY OF DEMAND FOR AIR TRAVEL

Historically, most analysts found the elasticity of demand for business travel to be inelastic with respect to yields (or fares) and elastic with respect to an income variable, most commonly real gross domestic product (GDP). Since 1988, growth rates in total enplanements have slowed. Figure 1 shows the actual growth in total passenger enplanements compared with the predicted growth using a regression equation based on 1969–1987 data (*4*). The gap that starts in 1988 reaches about 10 percent by 1993 and declines to about 6% in 1994. (If log linear equations are used, the difference between forecast and actual is over 20%.) Most of the 1994 growth in enplanements, however, was accounted for by short haul trips and discount fares. Data from passenger surveys (*3*) suggest that business enplanements as a percentage of total enplanements declined about 5 percentage points over the late 1980s and early 1990s.

To test the hypothesis that the relationship between business air travel and GDP has changed, we conducted an econometric analysis using the regression equations shown in Table 1. From 1988 onward, a dummy variable is used. If this variable is significantly different from zero (a t static greater than 1.8 at the 95 percent significance level), the hypothesis of a change in the relationship is not rejected. For both the linear and log-linear models, the dummy variable is significant, indicating that such a change in the business air travel elasticity of demand has occurred.

Time series data for more years are available for total passenger enplanements. Additional tests are made using these data, and they also support the hypothesis that significant changes in the demand elasticity relationships occurred at the end of the 1980s. Table 2 presents the estimation results for linear and log-linear models that com-

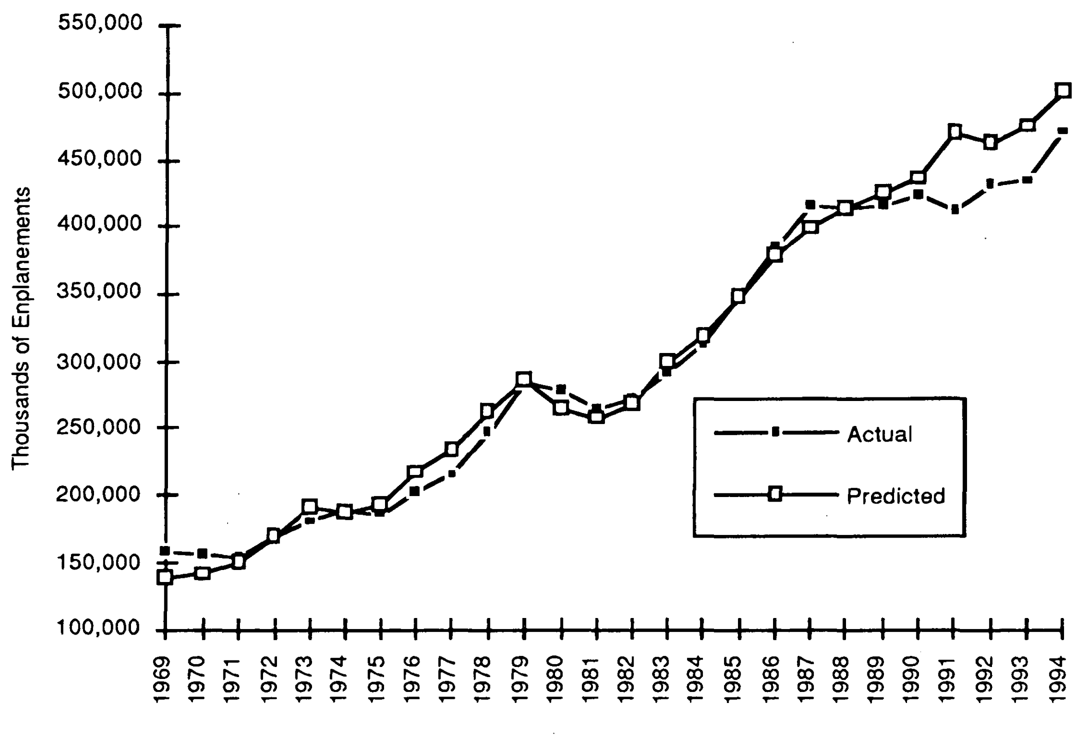


FIGURE 1 Actual versus predicted total domestic passenger enplanements: 1969–1994.

pare the 1969–1987 period to the 1988–1994 period. A test to determine if the coefficients are significantly different (*7*) is conducted for both models. The results, summarized in Table 3, indicate a difference in coefficients at the 95 percent level for both the linear and log-linear models, and a difference in coefficients at the 99 percent level for the log-linear model. We also tested the hypothesis using dummy variables for the 1988–1994 period. For both the linear and log-linear models, the dummy variables are significant at the 95 percent level, and at the 99 percent level for the log-linear model.

Econometric analysis definitely supports the contention that a major change has occurred in the functional relationship between business travel and traditional explanatory variables, GDP, and yield. This shift indicates that business enplanements, while continuing to grow with the economy, will be growing at a rate lower than that of GDP or similar variable.

Preliminary data are uncertain about the change in passenger enplanements in 1994. Surveys of business travelers suggest business travel will be up, but often travel budgets are the same or lower. Many companies report that they will be increasing the number of airline trips but spending less on air fares because they have implemented cost control and travel management policies (*8*).

INDUSTRY SPECIFIC ANALYSIS

Major Purchasers of Air Transportation

As shown in Figure 2, the manufacturing industries account for less than 20 percent of business air travel expenditures. Federal, state,

TABLE 1 Estimated Elasticities of Demand for Business Air Travel, 1977–1992

Equation	R^2	F-Statistic	GDP Elasticity	Yield Elasticity	Dummy Variable†
Linear	.985	99.78	1.53	-0.13	-276.26
			(6.4)	(-1.1)	(-2.0)
Log Linear	.982	79.16	1.65	-0.18	-0.07
			(6.0)	(-0.9)	(-2.0)

† Set equal to zero for years 1977 to 1988, and equal to 1 for 1989 to 1992.
Note: t-statistics given in parenthesis.

TABLE 2 Estimated Elasticities of Demand for Total Air Travel, 1969–1994

Time Period	Adjusted R2	F Statistic	GDP Elasticity	Yield Elasticity	Dummy Variable†
Linear Equations					
1988-1994	0.41	3.06	0.61	-0.21	
			(1.12)	(-0.50)	
1969-1987	0.98	384.76	1.25	-0.32	
			(8.18)	(-2.99)	
1969-1994	0.98	648.83	1.03	-0.39	
			(6.66)	(-3.07)	
1969-1994	0.98	450.87	1.19	-0.34	-20,097
			(6.92)	(-2.80)	(-1.79)
Log-Linear Equations					
1988-1994	0.40	3.04	0.58	-0.23	
			(1.03)	(-0.59)	
1969-1987	0.98	559.33	1.87	-0.41	
			(12.83)	(-2.47)	
1969-1994	0.97	451.49	1.76	-0.19	
			(8.32)	(-0.78)	
1969-1994	0.98	495.66	1.91	-0.31	-0.14
			(11.22)	(-1.62)	(-3.93)

† Dummy variable equals 0 for 1969 to 1987, and 1 for 1988 to 1993. A significant value indicates that an adjustment to the equation occurred during the second time period.
Note: t-statistics given in parenthesis.

and local government sectors account for about 12% of business air travel. The remaining two-thirds of business air travel is primarily in the services sectors, including wholesale and retail trade, finance, insurance, and real estate, and a broad range of other services such as management consulting, legal, medical, and educational services. Telecommunications expenditures (discussed in the section below) are more highly skewed toward the communications (about a third of expenditures on communications come from other communications industries or companies), and are less likely to be affected by the downturn in aerospace and defense and declines in the number of manufacturing jobs.

Using BEA data (*4*), we identified the top 40 out of approximately 480 industrial sectors that accounted for 80 percent of business expenditures on business air travel in the late 1980s. (See Table 4.) This section evaluates these industries in terms of their past and future growth prospects, because to a considerable extent, the fortunes of these 40 sectors dictate the fortunes of the air industry.

Growth Prospects

As a whole, the top 40 sectors are forecast by the BLS (*5*) to grow slower than the national average. For the decade of the 1990s, the median growth rate in employment for these industries is 1.0 percent and the average growth in real output is 2.1 percent. These compare with 1.3 and 2.7 percent, respectively, for the U.S. economy. Only 10 of the 40 top air travel industries are forecast to have faster job growth between 1992 and 2005 compared with their job growth during the period 1979–1992.

The top 10 business air travel sectors include the U.S. Department of Defense, which is undergoing cutbacks in funding and personnel; the U.S. Post Office, which is faced with increasing competition from the private sector, E-mail and facsimile machines; and public education, which is suffering from financial problems in many parts of the country. Several of the top sectors are considered to be high growth ones, at least in terms of employment. These include management consulting and retail trade. High growth manufacturing sectors, including semiconductors and computers, are also among the top industries. Although some growth in business air travel is expected from the manufacturing sectors, the emphasis placed on cost control could easily keep expenditures level, continue downward pressure on yields, and moderate the growth in enplanements.

Overall, the composition of industries that account for 80 percent of business air travel is changing, and future shifts will emphasize the trend toward the service sectors being the primary business air travel users.

TABLE 3 Test for Equality between Coefficients

Model	F Ratio	Reject Null Hypothesis at 5% Significance Level†	Reject Null Hypothesis at 1% Significance Level†
Linear	3.80	Yes	No
Log linear	13.06	Yes	Yes

† Null hypothesis is that the coefficients for the 1969 to 1987 period are equal (not significantly different from) the coefficients for the 1988 to 1993 period. For 5%, the F ratio must exceed 3.10 to reject the null hypothesis; for 1% the F ratio must exceed 4.94.

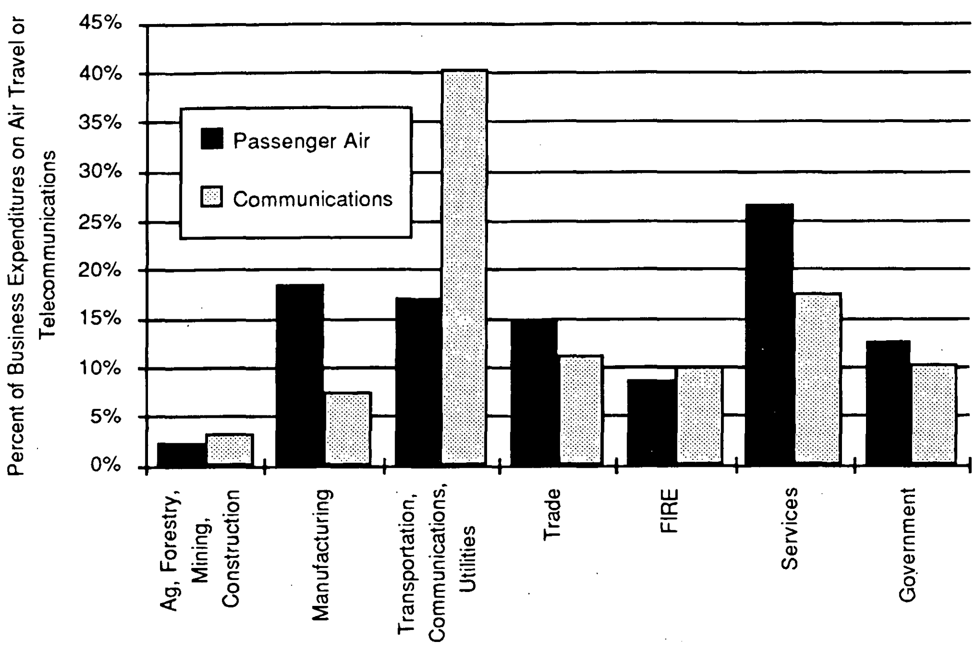


FIGURE 2 Distribution of air travel and telecommunications expenditures by sector.

USE OF TRAVEL MANAGERS

There has been a continued increase in the number of businesses using travel agents and travel managers to help control costs. The percentage of corporations that have corporate travel managers has grown from 7.5 to 38% between 1982 and 1993 (*9*). Nearly 80% of companies surveyed that spend more than $5 million on travel and entertainment (T&E) have such a manager. The role of travel manager has become more important as companies take steps to control travel and formalize policies. These managers generally report to a corporate administrative office.

Data from the 1991 *Travel Weekly* survey indicate that 23% of corporate clients of travel agencies had written guidelines or policies that year. By 1994, this percentage increased to 38%. The major focus of the policies is on air travel. The percentage of agency bookings coming from corporate travel managers or coordinators increased from 9% in 1991 to 12% in 1994 (*10*). The American Express survey found that 64% of companies with 100 employees or more had formal written travel guidelines. Large companies are much more likely to have policies: 96% of companies with T&E budgets over $5 million and 90% of companies with budgets from $1 million to $5 million report that they had formal written guidelines in place, compared with only 28% of companies with T&E budgets under $100,000.

Variation is wide among companies and industries in terms of travel policies, cost control, and use of telecommunications. Companies in manufacturing and engineering industries are generally the most cost conscious. Any company, however, that operates in a very competitive environment carefully scrutinizes air travel and looks for ways to control costs. At the other extreme, consulting, legal, some financial, and similar industries are lax in implementing and enforcing policies and are not aggressive in seeking out the lowest possible air fare. The type of trip most likely to be restricted is that involved with meeting other employees of the same company. Conversely, the type of trip least likely to be restricted is one involving sales calls to existing or prospective clients.

COMPETITION FROM TELECOMMUNICATIONS

All industries use telecommunications, and telecommunications expenditures generally exceed those of air transportation by about 2.5 to 1. The same is true for industrial sectors that are the mainstay of business air travel. (See Figure 3.) Many sectors that offer the greatest prospects for growth, however, also tend to be those that have the highest ratio of telecommunications expenditures to air travel expenditures: for example, trade, transportation, electronics and computers, and communications equipment and some business services. These industries are among those most likely to embrace telecommunications as an accepted means of doing business.

Other studies support the growing use of telecommunications. One indicates the extent of substitution should be 5 percent by 2000 and 25 percent by 2010 (*2*). Clearly substitution will depend on the availability and cost of telecommunications versus air travel, and also the acceptance of telecommunications compared with face-to-face contact. Telecommunications costs will continue to decline relative to air travel costs. The ability of communications to replace

TABLE 4 Estimated Expenditures on Air Travel by Selected Industries, 1977, 1982, and 1987

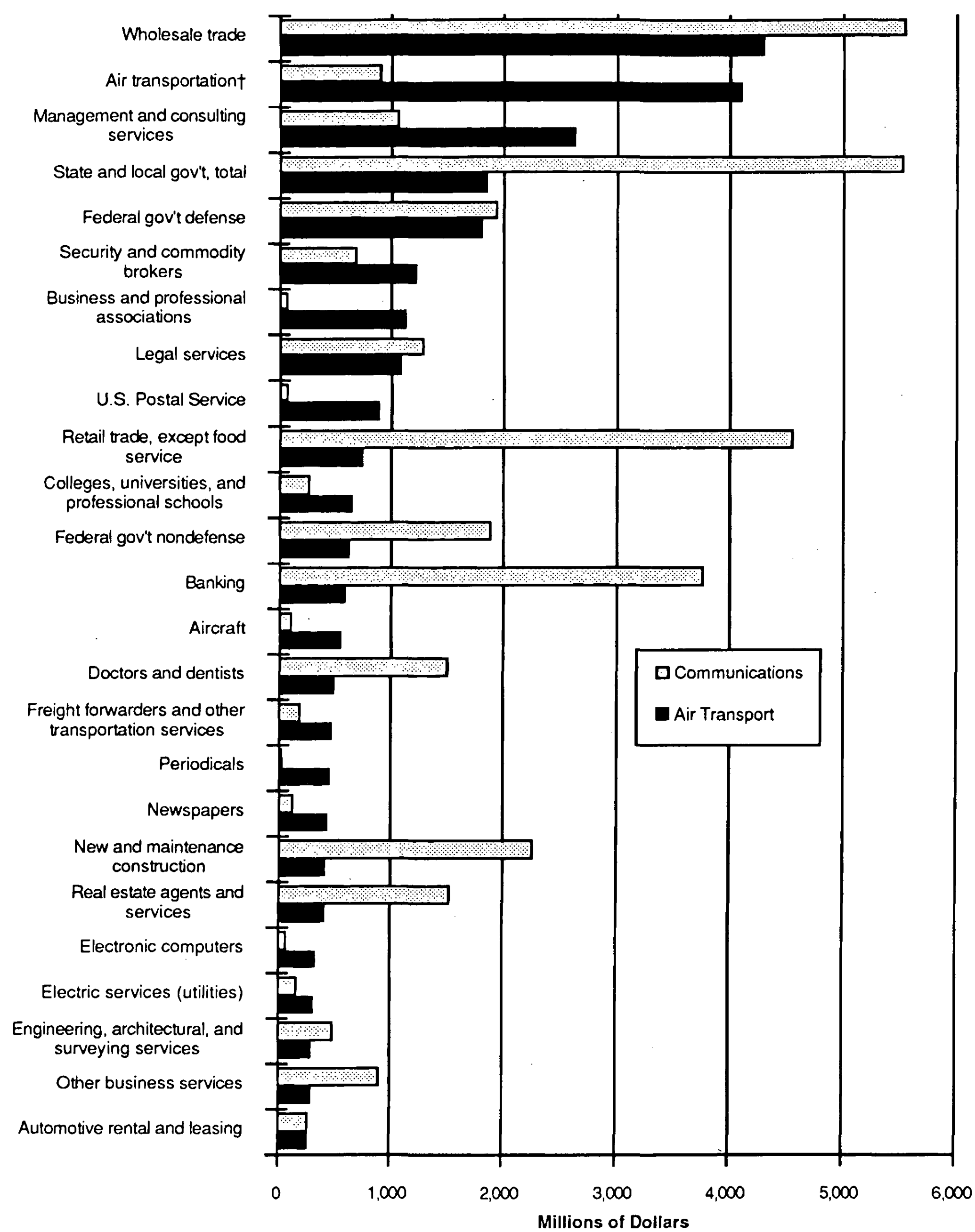
	1977	1982	1987	1982-87 Growth rate
	Millions of Dollars			
Wholesale trade	1,038	1,950	4,307	17%
Air transportation†	867	1,396	4,113	24%
Consulting services	316	773	2,641	28%
State and local government	785	1,210	1,866	9%
Federal government, defense	614	1,484	1,817	4%
Security and commodity brokers	124	647	1,243	14%
Associations	9	560	1,141	15%
Legal services	184	248	1,097	35%
U.S. Postal Service	460	695	906	5%
Retail trade	325	707	763	2%
Colleges, universities	187	291	664	18%
Federal government, nondefense	279	422	648	9%
Banking	90	181	599	27%
Aircraft	1,593	435	569	6%
Doctors and dentists	84	164	509	25%
Freight forwarders and other transportation services	98	200	483	19%
Periodicals	87	199	467	19%
Newspapers	225	500	445	-2%
Construction	222	296	433	8%
Real estate	98	219	418	14%
Electronic computers	121	481	341	-7%
Electric services (utilities)	96	229	325	7%
Engineering services	196	244	310	5%
Other business services	44	88	305	28%
Insurance carriers	130	283	288	0%
Other membership organizations	60	212	283	6%
Computer and data processing services	121	112	263	19%
Motor freight transportation and warehousing	56	118	232	14%
Accounting, auditing and bookkeeping, and	93	67	229	28%
Insurance agents, brokers, and services	47	91	205	18%
Radio and TV broadcasting	49	95	200	16%
Credit agencies other than banks	53	124	191	9%
Labor organizations, civic, social, and fraternal	58	98	184	13%
Communications except radio and TV	50	122	183	8%
Motor vehicles and car bodies	106	295	177	-10%
Industrial inorganic and organic chemicals	129	118	170	7%
Computer peripheral equipment			166	
Aircraft and missile engines and engine parts	77	147	165	2%
Agricultural, forestry, and fishery services	71	137	164	4%
Commercial printing	60	111	143	5%
Total business and government	12,163	21,912	35,526	10%
Personal consumption	12,769	20,574	29,349	7%
Exports	2,146	5,691	10,186	12%
Imports	-2,233	-3,931	-5,711	8%
Total industry output	24,846	44,245	69,350	9%

† Air Transportation includes imputed value of services provided by one airline to another.
Source: U.S. Department of Commerce, Bureau of Economic Analysis.

face-to-face meetings may depend, to a large measure, on the underlying reason for air travel. Discussions with current users of teleconferencing suggest most of the existing applications are for intracompany meetings or for meetings involving companies that are working together on specific projects. Sales calls still generally are held face-to-face, and communications technologies have yet to provide an alternative for large-scale conferences, conventions, and trade shows.

About half of business travel is for meetings, conventions, and trade shows (*10*). The remainder of business travel is fairly evenly divided between intracompany business and intercompany business. The most likely candidate for replacement of business air travel is intracompany business, or about 25 percent of air travel. Discussions with travel representatives in several U.S. corporations support the trend toward substituting communications for intracompany meetings. Several companies reported they have written policies restricting air travel, especially for meetings that only involve other employees. Not all intracompany travel can be substituted, for much of it requires physical presence, such as repair or installation of equipment of programs.

The possible small substitution of communications for business air travel (*3*) and the forecasted 5 percent substitution by 2000 are consistent with the regression equations presented previously in this report. They are also consistent with our understanding of the size and role of intracompany travel as a percentage of the total. Whether or not communications can reach 25 percent or more substitution will depend on technologies, customer acceptance, and costs, all of which are still major unknowns.



† Air Transportation includes imputed value of services provided by one airline to another.
Source: U.S. Department of Commerce, Bureau of Economic Analysis, *1987 Input Output Tables.*

FIGURE 3 Passenger air transportation and communications expenditures for selected industries, 1987. †Air transportation includes imputed value of services provided by one airline to another. Source: U.S. Department of Commerce, Bureau of Economic Analysis, *1987 Input Output Tables*, 1987

CONCLUSIONS

There has been a definite downward shift in business air travel, as substantiated by econometric analysis. The downward shift started in 1988, at a time when the economy started into a recession and businesses began corporate restructuring and downsizing. Recent data confirm that the 1993 recovery did not produce the rebound that would be expected with previous demand elasticities.

We identified about 40 industrial sectors that account for 80 percent of business air travel expenditures. We examined these businesses for several factors, including growth prospects and willingness to use telecommunications. The results of this analysis support the contention that business air travel will not be as strong in the 1990s and in previous decades.

- Many of the traditional business travel industries are not performing well or are forecast to grow slower than the national average. Among these industries are defense, aerospace, and the U.S. Post Office.
- Most of the important business travel sectors spend more on telecommunications than air travel. Through anecdotal evidence, it is clear many of the larger companies are frequent users of new communications technologies, at least for intracompany meetings. Indeed, several companies have already mandated the use of telecommunications whenever reasonable or feasible.
- Changes that are slowing the growth of air travel include downsizing of middle management; increased control over corporate travel; and the spread of telecommunications, electronic mail, and electronic data interchange (EDI) for communications and contact with suppliers, customers, and employees. In many industries, the use of multiple communications technologies is changing how business people interact with each other.

The net affect of changing industry structure, cost control, and telecommunications on business air travel is uncertain. The industry shift, away from manufacturing and toward services should help increase enplanements, because of the faster rate of growth in sales and employment displayed by the service sectors. However, travel management and telecommunications are likely to place downward pressure on business travel growth with the result that overall business enplanements and expenditures on air travel will not grow as fast as in the 1980s.

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Multiple Airport Systems in the United States: Current Status and Future Prospects

MARK HANSEN AND TARA WEIDNER

This study examines existing multiple airport systems (MASs) in the United States and assesses the prospects for new MASs in the future. Using FAA and other data, we identify 14 MAS regions in the United States, which account for 2.8 percent of all communities with commercial air service and 43 percent of total enplaned passengers. The 14 MASs divide into roughly five clusters, based on their market size, and the concentration of traffic within them. Twelve of the MAS regions are "hubs" as defined by the FAA, whereas the others are MASs because of exceptional circumstances. Analyzing the 11 "large" and "medium" hub MASs, we model concentration, as measured by the Herfindahl concentration index, and find that it decreases with regional origin and destination (O&D) traffic and increases with connecting traffic. Next we use a binary logit model to find determinants of MAS status. We find that the probability of a region being served by a MAS increases with the total traffic in the region, with some evidence that the probability decreases with the ratio of total enplanements to O&D traffic. Using the two models and FAA forecasts for the year 2000, we find that 13 regions currently served by a single airport have a significant MAS probability, and that about half of these are likely to be fairly unconcentrated MASs. We conclude that the U.S. air transport system has reached the point in which MASs could become increasingly common, and in which airports could, therefore, become a competitive industry in many regions.

Many of the world's larger urban areas are served by more than one commercial airport. Such multiple airport systems (MASs) offer several advantages over single airport systems (SASs). Access costs are reduced, since travelers can choose the airport closest to their true origin or final destination. This is not only more convenient, but also reduces social costs of vehicle travel, such as congestion and emissions. In addition, airports in a MAS will, *ceteris paribus*, be smaller than a single airport serving the same region. This implies reduced walking times, less costly parking facilities, and a less formidable wayfinding challenge for airport users. In short, when a region is served by a MAS, the cost and inconvenience of getting to the airport, and of getting through the airport, are reduced.

More generally, a MAS offers the possibility for increased consumer choice and competition in the supply of airport services. As Garrison and Gifford (*1*) point out, airline deregulation has given passengers more choice with regard to airlines and service classes, but commercial airports continue to operate as state-run monopolies in most areas. The lack of airport choice, combined with the high level of standardization among the products of most airlines, sharply limit opportunities for air travelers to make choices and thereby reveal their service preferences. The mere existence of alternative airports ensures somewhat greater consumer choice. If the airports actively compete to provide the most attractive amenities and services, consumers may benefit still further. Finally, airport competition might allow less government interference in airport pricing and investment decisions. Creager (*2*) argues that such airport deregulation is the natural counterpart of airline deregulation.

Air Transportation Research Center, Institute of Transportation Studies, University of California, Berkeley, Calif. 94720.

Despite these advantages, MAS development is opposed by a number of factors. Travelers value service frequency, which is obviously maximized when all flights leave from a single airport. There are also certain fixed station costs that encourage airlines to serve only one airport in a region. Indivisibilities associated with other airport assets—runways, control towers, and so forth—may exert a similar influence. A third consideration favoring a SAS is the economies of hubbing, which depend on being able to fly passengers in and out of a single hub airport. Finally, there are political and institutional barriers to the transition from a SAS to a MAS. These include resistance from incumbent airlines, political opposition to building a new airport, and risk averseness on the part of airport financiers.

This report argues that, the above factors notwithstanding, conditions are ripe for a period of MAS development in the United States. We begin by inventorying existing MASs in the continental United States (Section 1). Next, in Section 2, we analyze the concentration of passenger traffic in MASs, an indication of whether they are truly competitive. In Section 3, we consider the factors that determine whether an urban region is served by a MAS or a SAS. Then, in Section 4, we assess the potential of existing SASs to become MASs. Section 5 offers conclusions.

1. MULTIPLE AIRPORT SYSTEMS: AN INVENTORY

This section identifies urban regions served by a MAS (MAS regions) in the continental United States. The identification of these regions involves a two-step process. Initially we identify regions with more than one commercial airport in the classification structure defined by the FAA (*3*). However, this list omits certain MAS regions, while including others that, while nominally served by a MAS, have one airport that is so dominant that for all intents and purposes it is a SAS. Therefore, we adjust the FAA list by consolidating regions into MASs, and redesignating certain highly concentrated MASs as SASs.

Table 1 shows the 13 MASs recognized by the FAA in 1991 (3). This list includes all urban regions (termed "Communities" by the FAA) served by two or more airports with scheduled commercial air passenger service. We exclude cases in which the secondary airports provide only air cargo, nonscheduled passenger, or general aviation service, as well as regions located outside the continental United States.

TABLE 1 MAS Airport Set Development

Region	FAA Airport Set	CMSA/MSA Additional Airports	Enplanement Concentration Index	MAS
Chicago, IL	ORD, MDW, CGX		0.818	X
New York City, NY	LGA, JFK	EWR, ISP, SWF, HPN	0.313	X
Los Angeles, CA	LAX, SNA, BUR, LGB	ONT, PSP, OXR, PMD	0.499	X
Dallas/Ft. Worth, TX	DFW, DAL		0.804	X
San Francisco, CA	SFO, OAK, CCR	SJC, STS	0.529	X
Washington, DC	DCA, IAD	BWI (1)	0.346	X
Miami, FL	MIA, FLL		0.608	X
Houston, TX	IAH, HOU, EFD		0.561	X
Detroit, MI	DTW, DET		0.937	X
Santa Barbara, CA	SBA, SMX		0.929	X
Oshkosh/Appleton, WI	ATW, OSH		0.830	X
Seattle, WA	SEA, BFI		1.000	(2)
Tampa, FL	TPA, PIE		0.999	(2)
Philadelphia, PA	PHL	TTN	0.994	(2)
Cleveland, OH	CLE	CAK	0.907	X
Norfolk, VA	ORF	PHF	0.911	X
Pensacola, FL	PNS	VPS	0.717	X

(1) Within 48 km (30 miles) of DCA in Washington DC MSA, an FAA "large hub" community.

(2) Not considered MAS due to extremely high enplanement concentration.

Note: Index refers to Herfindahl index of airport concentration, the sum of the squared airport market shares of the given passenger activity type.

Sources: FAA Airports - FAA Airport Activity Statistics, 1991.

CMSA/MSA Boundary - U. S. Bureau of the Census, 1990.

The set of MAS regions defined by the FAA is not complete. Several major metropolitan areas are divided into multiple communities. To rectify this, the FAA definition was modified to allow consolidation of airports located within the same 1990 Metropolitan Statistical Areas (MSA) or Consolidated MSA (CMSA) (4). This action allowed for the consolidation of MASs in major metropolitan areas as well as introducing four new MAS regions. Table 1 identifies these changes.

Additionally, an analysis was made of airports near all FAA "large hub" communities. Baltimore-Washington International (BWI) Airport emerged as a special case based on its close proximity to the Washington, D.C. MSA airports (48 km, or 30 mi, from National Airport) and large traffic relative to these airports (27 percent of the combined total). Furthermore, these airports have been planned cooperatively for many years, and the Baltimore and Washington MSAs were in fact combined into a CMSA in 1991 (*4*). Consequently, as shown in Table 1, we consolidate BWI with National and Dulles Airports to form a MAS serving the Baltimore-Washington region.

A final review reveals that our set of MASs includes several in which a second airport handles a tiny amount of traffic relative to the primary airport. Because of this large gap in activity, these communities effectively function as single airport systems. The Herfindahl concentration index (HCI) was used as a measure of the degree to which passenger activity is concentrated at a single airport within the region. It is calculated as the sum of the squared traffic shares of each airport in the MAS. ("Traffic" can mean enplaned passengers or origin and destination (O&D) passengers. In identifying MASs with excessive concentrations, we use the former.) For a SAS, the HCI is 1.0. For a MAS where traffic is evenly divided among N airports, the HCI is $1/N$. Within our set of MASs, the HCI ranges from 0.9998, for Seattle, where one airport is highly dominant, to 0.313 for New York. Three of the MASs—Seattle, Philadelphia (HCI = 0.999), and Tampa (HCI = 0.994)—have concentrations well above that for any of the others (the next highest is Santa Barbara, Calif., with an HCI of 0.929). These three MASs were therefore redesignated SASs for purposes of our analysis.

We summarize the above discussion by offering a proposed definition of a MAS. In general we define a MAS as two or more airports operating in a contiguous metropolitan area in such a way as to form an integrated airport system. This integration is largely evident in the airports' competition for local passengers. More precisely, we define a MAS as consisting of two or more airports with scheduled passenger enplanements, and which satisfy both of the following criteria:

- Each airport is included in the same community by the FAA(3) *or* within 50 km (30 mi) of the primary airport of an FAA-designated "large hub" community, *or* each airport is in the same MSA or CMSA (*4*);
- The Herfindahl concentration index for the airports is less than 0.95.

Table 2 identifies the 14 MASs within the continental United States, based on the above definition. Enplanement and O&D passenger statistics for the MASs and their constituent airports are also presented. Most MASs have high traffic levels, with the majority exceeding 10 million enplanements per year. However, there are also some small MASs, three with traffic levels under 0.5 million. The MAS consists of two airports in eight cases, three airports in

TABLE 2 Existing Multiple Airport Systems

Region and MAS Airports	FAA Hub	Airport Code	1991 Scheduled Enplanements Total	1991 Scheduled Enplanements Index	1991 Domestic O&D Enplanements Total	1991 Domestic O&D Enplanements Index
1 CHICAGO, IL	L		29,040,932	0.818	12,644,170	0.783
O'Hare International		ORD	26,098,065		11,078,080	
Chicago Midway		MDW	2,935,166		1,564,190	
Meigs Field		CGX	7,701		1,900	
2 NEW YORK CITY, NY	L		27,918,360	0.313	19,806,200	0.329
Newark		EWR	9,645,295		7,197,470	
La Guardia		LGA	9,121,466		7,998,160	
John F. Kennedy International		JFK	8,207,264		3,601,360	
Islip/Macarthur		ISP	410,150		452,000	
Newburgh		SWF	355,822		350,340	
White Plains		HPN	178,363		206,870	
3 LOS ANGELES, CA	L		26,276,420	0.499	20,113,310	0.327
Los Angeles International		LAX	18,069,981		12,101,410	
Ontario/San Bernadino/Riverside		ONT	2,831,551		2,729,010	
Orange County/John Wayne		SNA	2,544,596		2,450,970	
Hollywood-Burbank		BUR	1,821,400		1,803,720	
Long Beach		LGB	648,541		636,130	
Indio/Palm Springs		PSP	330,741		334,150	
Oxnard/Ventura		OXR	20,643		39,390	
Palmdale/Lancaster		PMD	8,967		18,530	
4 DALLAS/FT. WORTH, TX	L		25,416,828	0.804	9,286,950	0.635
Dallas/Ft. Worth International		DFW	22,625,338		7,052,420	
Love Field		DAL	2,791,490		2,234,530	
5 SAN FRANCISCO, CA	L		20,149,914	0.529	14,464,640	0.465
San Francisco International		SFO	14,007,424		9,130,230	
San Jose Municipal		SJC	3,148,622		2,404,100	
Metropolitan Oakland		OAK	2,953,058		2,853,090	
Santa Rosa/Sonoma County		STS	35,675		65,690	
Concord/Buchanan Field		CCR	5,135		11,530	
6 WASHINGTON, D.C.	L		15,548,897	0.346	10,643,900	0.394
Washington National		DCA	6,602,686		5,692,600	
Dulles International		IAD	4,706,395		2,452,140	
Baltimore, MD		BWI	4,239,816		2,499,160	

three cases, and five, six, and eight airports in the remaining three cases. Enplanement distributions in the MASs are fairly concentrated, with half having HCI values over 0.8, and only two with HCIs under 0.5—the value for a two-airport MAS with evenly divided traffic. The concentration is also evident in the fact that in eight of the MASs, the busiest airport has more than five times as many enplanements as the second busiest. In no case, moreover, does a MAS include more than four airports with an enplanement level more than 10 percent that of the busiest airport in the MAS.

The MAS regions are compared to the FAA "hub" communities and the U.S. system as a whole in Table 3. The 14 MAS communities account for 43 percent of all U.S. passenger activity, even though they represent less than 3 percent of the communities receiving scheduled air service. All but two of the MASs lie in FAA-defined "hub" communities—those with at least 0.5 percent of total U.S. enplanements. Indeed, 32 percent of the "large hub" communities, which together account for 56 percent of "large hub" enplanements, are served by a MAS. In addition, 7 percent of the "medium hub" communities and 2 percent of the "small hub" communities have MASs.

The 14 MAS regions are diverse. In order to understand the different types of MASs that have developed in the United States, these systems were classified. The classification is based on Figure 1, in which the HCI and traffic of each MAS is plotted. For comparison "large hub" and "medium hub" SASs, all with HCIs of 1.0, are also plotted. From this figure, five clusters of MASs are identified. These are characterized in Table 4.

Cluster 1, consisting of New York and Washington, D.C., is unique in its lack of a dominant airport. Enplanements are shared almost equally among three or more airports, as indicated by its low airport concentration indices ranging from 0.31 to 0.39. In contrast to the other MAS regions, these two exhibit more concentration in their O&D traffic than their total enplanements. This reflects the fact that hubbing activity has focused on airports that are somewhat less competitive for the local market—Newark in the case of New York and Dulles and BWI in the case of Washington. Congestion at one or more airports in the MAS limits the market share of any one facility.

Cluster 2 consists of five MAS regions, located in the South and West. These differ from the first group in that in each case one air-

TABLE 2 Existing Multiple Airport Systems (*continued*)

Region and MAS Airports	FAA Hub	Airport Code	1991 Scheduled Enplanements Total	Index	1991 Domestic O&D Enplanements Total	Index
7 MIAMI, FL	L		12,575,026	0.608	7,503,320	0.526
Miami International		MIA	9,212,517		4,609,900	
Ft. Lauderdale-Hollywood Int'l		FLL	3,362,509		2,893,420	
8 HOUSTON, TX	L		11,567,113	0.561	6,736,070	0.496
Houston Intercontinental		IAH	7,805,317		3,428,090	
W. Hobby		HOU	3,756,251		3,275,790	
Ellington Field		EFD	5,545		32,190	
9 DETROIT, MI	L		9,791,172	0.937	5,121,710	0.883
Wayne County		DTW	9,470,549		4,801,450	
Detroit City		DET	320,623		320,260	
10 CLEVELAND, OH	M		3,689,358	0.907	2,747,400	0.837
Hopkins International		CLE	3,508,196		2,502,300	
Akron/Canton		CAK	181,162		245,100	
11 NORFOLK, VA	M		1,222,110	0.911	1,196,100	0.837
Norfolk International		ORF	1,165,224		1,088,680	
Newport News/Patrick Henry Int'l		PHF	56,886		107,420	
12 PENSACOLA, FL	S		450,473	0.717	507,280	0.618
Pensacola Regional		PNS	373,688		376,770	
Ft. Walton Beach		VPS	76,785		130,510	
13 SANTA BARBARA, CA	---		207,892	0.929	263,890	0.798
Santa Barbara		SBA	200,269		233,820	
Santa Maria Public		SMX	7,623		30,070	
14 OSHKOSH/APPLETON, WI	---		135,199	0.830	173,720	0.820
Outagamie County/Appleton		ATW	122,515		156,310	
Wittman Field/Oshkosh		OSH	12,684		17,410	

Note: Index refers to Herfindahl index of airport concentration, the sum of the squared airport market shares of the given passenger type.

Sources: Enplanements - T3/T100 Report, ONBOARD Database, ODProducts Inc., 1991.
O&D - USDOT 10% Sample, Outbound Passengers, ODPLUS Database, ODProducts Inc., 1991.

port clearly dominates, resulting in a higher HCI, ranging from 0.50 to 0.61. However, secondary airports play a significant role in these MASs since the concentration indices are low compared to Clusters 3, 4, and 5. Indeed, the O&D traffic HCI for Los Angeles is very low, indicating the inability of any one airport to dominate the local market in such a far-flung urban landscape. Houston, although considerably smaller, is subject to much the same phenomenon. Although this group also contains higher density areas such as San Francisco and Miami, both of these have geographical features that encourage the dispersal of airport activity. In the case of the former, San Francisco Bay results in longer travel distances than the population density suggests, whereas the Miami region's location on a narrow coastal plain, and resulting elongated form, has a similar effect. As in the first cluster, airport capacity limitations may also reduce the concentration of enplanements.

The MAS regions in the third cluster, Dallas and Chicago, are distinguished by their role as major transfer points as the result of hub-and-spoke operations by air carriers. Because of the natural tendency for transfer activity to concentrate at a single airport, the enplanement HCI is higher: 0.64 to 0.82. The large number of transfer passengers at the primary airport results in a high service frequency which serves to attract most of the local traffic. However, the secondary airport in these regions is well located and attracts a reasonable share of the local passenger demand, decreasing the O&D HCI. These MASs are also subject to congestion, exacerbated by the traffic peaking due to connecting complex operations.

The fourth MAS cluster features a lower total enplanement level than the first three. The MASs in this group are also considerably more concentrated, with enplanement HCIs ranging from 0.91 to 0.94. All of these MASs consist of only two airports, with the dominant airport handling over 95 percent of the total passenger activity. This domination may be the result of the lower demand levels, higher densities, or less severe congestion problems.

The fifth and final cluster consists of MAS regions with very low traffic. These MASs are somewhat less concentrated than the fourth group, with enplanement HCIs ranging from 0.62 to 0.93. Two of the three result from unusual circumstances. Pensacola is dominated by military activity which has encouraged ancillary passenger service to develop at a second airport. Likewise, Appleton is the site of an airfield used by experimental aircraft. The Santa Barbara/Santa Maria MAS appears to be the result of these two formerly distinct regions growing together.

2. DETERMINANTS OF MAS CONCENTRATION

In this and the next section, we turn to statistical analysis of MASs in the United States. In this section, we analyze MAS concentration levels, whereas in Section 3 we investigate the determinants of MAS status.

TABLE 3 Comparative Activity Statistics

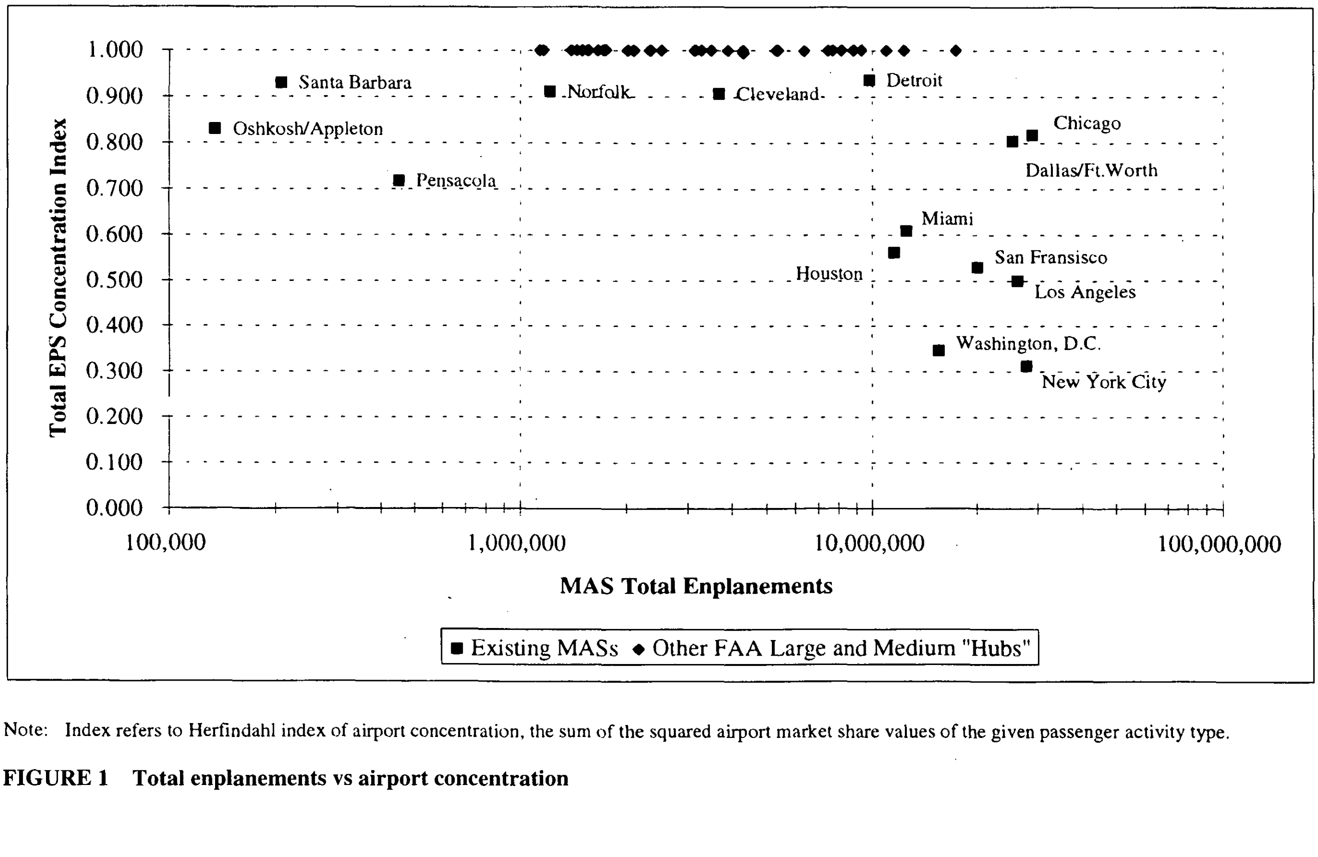
MASs as Percentage of:	Number of Communities	1991 Enplanements Total	Domestic	International	1991 Domestic O&D
Large Hub Communities	32.14%	56.39%	55.27%	75.23%	59.31%
Medium Hub Communities	7.41%	7.85%	7.91%	4.24%	7.93%
Small Hub Communities	1.82%	1.50%	1.54%	0.00%	2.03%
Non-Hub Communities	0.52%	2.06%	2.06%	0.00%	2.39%
Total Hub Airports	12.73%	45.00%	43.83%	68.36%	44.10%
Total All Airports	2.83%	43.24%	42.04%	68.26%	41.18%

Note: The definition of Multiple Airport System (MAS) communities consolidates several FAA "hub" communities.

We have already given considerable attention to the MAS concentration, as measured by the HCI. The concentration is important for several reasons. Since a SAS, by definition, has an HCI of 1, the HCI of a MAS measures how different it is from a SAS. The advantages and disadvantages of a MAS as compared with a SAS become more significant as the MAS concentration decreases. In a highly concentrated MAS, passengers from throughout the MAS region will use the primary airport, resulting in ground access costs comparable to a SAS. Likewise the primary airport of a highly concentrated MAS will be virtually as large as it would be in the case of a SAS. Also, for many destinations, the primary airport of a concentrated MAS is likely to be the only realistic alternative, depriving many or most air travelers of the choice that we have argued is one of the main benefits of a MAS. Finally, because a highly concentrated MAS is not very competitive, for most policy purposes it must be regulated as a monopoly. The potential gains from airport deregulation are therefore lost.

Having established that MAS concentration is important, we consider what factors may affect this variable. At a micro level, these factors will include anything that affects the distribution of traffic among MAS airports. These include a host of airport attributes, such as location and accessibility, capacity, use restrictions, traveler and travel agent awareness, and so on. These factors influence travelers' airport choices directly, and also indirectly through their effect on airline service supply decisions (*5*). Thus a complete representation of the processes determining MAS concentration would require a highly detailed analysis. There has been considerable work at this level (*6–9*), and more is ongoing, but here we want to paint with a broader brush.

At the macro level, we hypothesize that the level of concentration in a MAS is affected by three factors. First, as local (or O&D) traffic increases, we expect concentration to decrease. More local traffic will result in more markets in which nonstop service can be supported from more than one airport. Since service quality gains from flight frequency are diminishing, high local demand results in a reduced frequency advantage for the primary airport. Also, the stronger the local traffic base, the more willing airlines will be to serve more than one airport in the region. Finally, the larger the pri-



Note: Index refers to Herfindahl index of airport concentration, the sum of the squared airport market share values of the given passenger activity type.

FIGURE 1 Total enplanements vs airport concentration

TABLE 4 Multiple Airport System Community Characteristics

		Passenger Activity (millions)				Land Area	Airport Capacity	
	Number of	1991 EPS		1991 Dom. O&D		1984	FAA Delays (1)	
	Airports	Total	Index	Total	Index	Area (sqkm)	1990	2000
CLUSTER 1								
New York City, NY	6	27.918	0.313	19.806	0.329	19,834	X	X
Washington, D.C.	3	15.549	0.346	10.644	0.394	17,032	X	X
CLUSTER 2								
Los Angeles, CA	8	26.276	0.499	20.113	0.327	88,081	X	X
San Francisco, CA	5	20.150	0.529	14.465	0.465	19,174	X	X
Miami, FL	2	12.575	0.608	7.503	0.526	8,200	X	X
Houston, TX	3	11.567	0.561	6.736	0.496	18,521	X	X
CLUSTER 3								
Chicago, IL	3	29.041	0.818	12.644	0.783	14,659	X	X
Dallas/Ft. Worth, TX	2	25.417	0.804	9.287	0.635	18,122	X	X
CLUSTER 4								
Detroit, MI	2	9.791	0.937	5.122	0.883	13,481	X	X
Cleveland, OH	2	3.689	0.907	2.747	0.837	7,563		X
Norfolk, VA	2	1.222	0.911	1.196	0.837	4,447		
CLUSTER 5								
Pensacola, FL	2	0.450	0.717	0.507	0.618	4,362		
Santa Barbara, CA	2	0.208	0.929	0.264	0.798	7,117		
Oshkosh/Appleton, WI	2	0.135	0.830	0.174	0.820	3,670		

Sources:

Passenger Activity - ODPlus (T3/T100) and ONBOARD (10% Ticket Survey) databases, ODProducts, Inc., 1991. Index refers to Herfindahl index of airport concentration, the sum of the squared airport market share values of the given passenger activity type.

Land Area - U.S. Bureau of the Census for CMSA/MSA.

Delays - MAS contains airports to exceed 20,000 hours of delay in given year, Aviation System Capacity Plan, FAA, 1991/1992.

mary airport in the region gets, the more it is subject to diseconomies of scale such as longer walking distances or the need to build expensive parking structures.

Second, as connecting traffic increases, we expect concentration to increase. An airline with a connecting hub in a MAS will naturally consolidate this operation at one airport, since it is prohibitively costly and inconvenient to transport connecting passengers between airports. For similar reasons, interline connecting traffic is likely to concentrate at a single airport. If more than one airline operates a hub in a MAS, the situation is somewhat more complicated, since the advantages of being able to offer interline connections by using the same airport must be weighed against the traffic capture and product differentiation benefits from operating hubs at different airports. In many cases, however, the latter is not an option, since only one airport in the region has the capacity to handle the traffic surges resulting from connecting complexes.

Third, as the land area of the MAS region increases, we expect concentration to decrease. When the land area is greater, ceteris paribus, each airport will have a larger "captive" market area for whom it is by far the closest alternative. This will attract both passengers seeking convenience and airlines seeking a protected market niche.

To test these hypotheses, we estimated models of MAS concentration. The models are of the form:

$$\ln\left(\frac{\mathrm{HCI}}{1-\mathrm{HCI}}\right) = \alpha + \beta \cdot \ln(\mathrm{ODPAX}) + 5 \cdot \ln(\mathrm{ENP}) + \lambda \cdot \ln(\mathrm{AREA}) + \varepsilon \quad (1)$$

where

HCI = Herfindahl concentration index;
ODPAX = total MAS O&D passengers in the year 1991 (millions);
ENP = total MAS enplaned passengers in the year 1991 (millions);
AREA = land area of the region, in square miles;
ε = a stochastic error term;
α, β, δ, and λ = coefficients to be estimated.

The transformation of HCI in the above equation is used to convert a 0-1 variable to one whose range is $-\infty$ to $+\infty$. According to our hypotheses, β is negative, δ is positive (since an increase in ENP, controlling for PAX, implies an increase in connecting traffic), and λ is negative.

The model was estimated on the 11 MASs included in the first four clusters described above. The three MASs in the fifth cluster were excluded, since they are unusual cases whose behavior is unlikely to be captured by the same structural equation as the others. Also, data for these small MASs are suspect since reported O&D traffic exceeds reported enplanements, probably because the latter excludes commuter carriers. (We did estimate the model with all 14 MASs, obtaining similar coefficient estimates and significance levels, but with a slightly poorer fit.)

Estimation results appear in Table 5 which includes results for both the concentration of O&D traffic and enplanements. Both models have fairly good fits, with adjusted R^2 over 0.6. In both cases, the land area variable is statistically insignificant and of the wrong sign. This suggests that land area is a poor measure of the phenomenon it is intended to capture—the extent to which airports in the MAS have geographically protected market niches. The other variables have the expected signs. O&D traffic is statistically significant at the 5 percent level, whereas enplanements is significant at the 10 percent level (and, in three of the four models, almost significant at the 5 percent level). The O&D traffic coefficient has a larger magnitude than the enplanement coefficient. This is reasonable since an increase in O&D traffic implies an increase in enplanements, but according to the arguments above should nonetheless result in a net reduction in airport concentration. Finally, it is notable that connecting traffic is positively associated with O&D traffic as well as enplanement concentration. This implies that connecting traffic, itself tending to concentrate for reasons stated previously, pulls O&D traffic along with it.

3. DETERMINANTS OF MAS STATUS

Next we consider whether MAS status, like MAS concentration, can be explained at a macro level. Given a region, can we predict whether it is served by a MAS or a SAS? We already have some evidence on this question from Table 3, which shows a strong correlation between hub class and MAS status. Further evidence is obtained from categorizing "large" and "medium hubs" by enplanement level. Of the 51 regions (taking into account our consolidations) defined as "large" or "medium hubs" by the FAA (that is, with enplanements of 0.25 percent or more of the national total), all those with 20 million enplanements and 50 percent of the "hubs" with 10–20 million enplanements are MAS regions, whereas 90 percent with under 10 million enplanements are served by single airports.

In addition to total traffic, it is reasonable to suppose that other factors that affect MAS concentration also affect MAS status. Indeed, we have already argued that a SAS can be viewed as an extremely concentrated MAS. Therefore, in light of the findings from the last section, we expect regions with a higher proportion of O&D traffic to be more likely candidates for MAS status.

On the other hand, there is a qualitative difference between a SAS and even a highly concentrated MAS. In the latter case, a second commercial airport exists, and in the first it does not. The barriers to this transition (in either direction: opening a commercial airport, or closing it) are considerably higher than those to changing the distribution of activity among existing airports. Thus we expect that at any given time, the MAS status of a region will depend on past history as much or more than current conditions. This will introduce considerable noise into the analysis of a snapshot of the system at a given time.

Notwithstanding this problem, we used a binary choice model to analyze the MAS status of the 51 large and medium hub airports. The form of the model is:

$$P_i\,(MAS) = \frac{e^{\theta_k X_{ik}}}{1 + e^{\theta_k X_{ik}}} \qquad (2)$$

where

$P_i(\text{MAS})$ = probability that region i is a MAS region;
X_{ik} = a vector of regional characteristics;
θ_k = a vector of coefficients to be estimated.

For the X_{ik} we tried various combinations of enplanements, O&D traffic, their ratios, and their logs. Estimation results for three of the better performing models are summarized in Table 6. The models have reasonable explanatory power, with ρ^2 (with respect of constants) approaching 0.5, and correct predictions for just over half of the MAS outcomes, and 90 percent of all outcomes. The models confirm the relationship between total traffic and MAS status already observed. They also lend some support to the hypothesis that MAS status is related to the O&D/connecting composition of traffic, although this effect is of marginal statistical significance.

TABLE 5 Estimation Results, Herfindahl Concentration Index Models

Independent Variable	Dependent Variable: O&D Traffic HCI (Transformed)		Dependent Variable: Enplanement HCI (Transformed)	
Constant	1.90	2.56	1.87	1.89
	(3.5)	(4.1)	(3.2)	(3.7)
ln(Enplanements)	2.12	1.94	1.57	1.57
	(2.4)	(2.2)	(2.0)	(2.2)
ln(O&D Traffic)	-3.75	-3.21	-2.63	-2.62
	(-3.2)	(-3.2)	(-2.6)	(-3.2)
ln(Land Area)	0.48	--	0.01	--
	(0.9)	--	(0.0)	--
R^2 (Adjusted)	.64	.65	.61	.66

Note: t-statistics in parentheses.
Land Area is in units of sqkm

TABLE 6 Estimation Results, MAS Status Model (Binary Logit)

Independent Variable	Model 1	Model 2	Model 3
Constant	-3.66	-0.93	-8.04
	(-4.1)	(-0.5)	(-2.1)
Total Enplanements (Millions)	0.27	0.41	0.38
	(3.2)	(2.6)	(2.6)
O&D Traffic/Total Enplanements	--	--	5.15
	--	--	(1.3)
Total Enplanements/O&D Traffic	--	-2.41	--
	--	(-1.5)	--
ρ^2 (zero)	0.56	0.62	0.59
ρ^2 (constants)	0.41	0.49	0.46
Log Likelihood	-15.59	-13.60	-14.36
No. Correct MAS Predictions	6/11	7/11	6/11
No. Correct SAS Predictions	39/40	40/40	39/40
Total Correct Predictions	45/51	47/51	45/51

Note: t-statistics in parentheses.

The latter is not surprising if one considers the data. In 1990, the nation had five regions with over 10 million enplanements and an enplanement/O&D ratio over 2—Chicago, Dallas, Denver, Atlanta, and St. Louis. Of these, the first two are MAS regions and the others are served by a SAS. All the regions with less than 10 million enplanements in 1990 and a enplanement/O&D ratio over 2 have SASs but so do most other regions with traffic below this threshold. Thus, although the evidence that connecting traffic affects MAS concentration is quite strong, it is far less definitive in the case of MAS status.

4. POTENTIAL MULTIPLE AIRPORT SYSTEMS

The models developed in Sections 2 and 3 were used to investigate the potential for additional multiple airport systems development over the next two decades. To do this, we calculated the MAS probability of each of the 40 "large" and "medium hubs" currently served by a single airport. We did this both for 1990 and, using the FAA forecasts (*10*) for the year 2000. For purposes of comparison, the probabilities were also calculated for existing MASs.

Figure 2 shows the 1990 and 2000 results for all existing MASs and those SASs with a nontrivial MAS probability. The 1990 results show that, among the existing MASs, Detroit, Cleveland, and Nor-

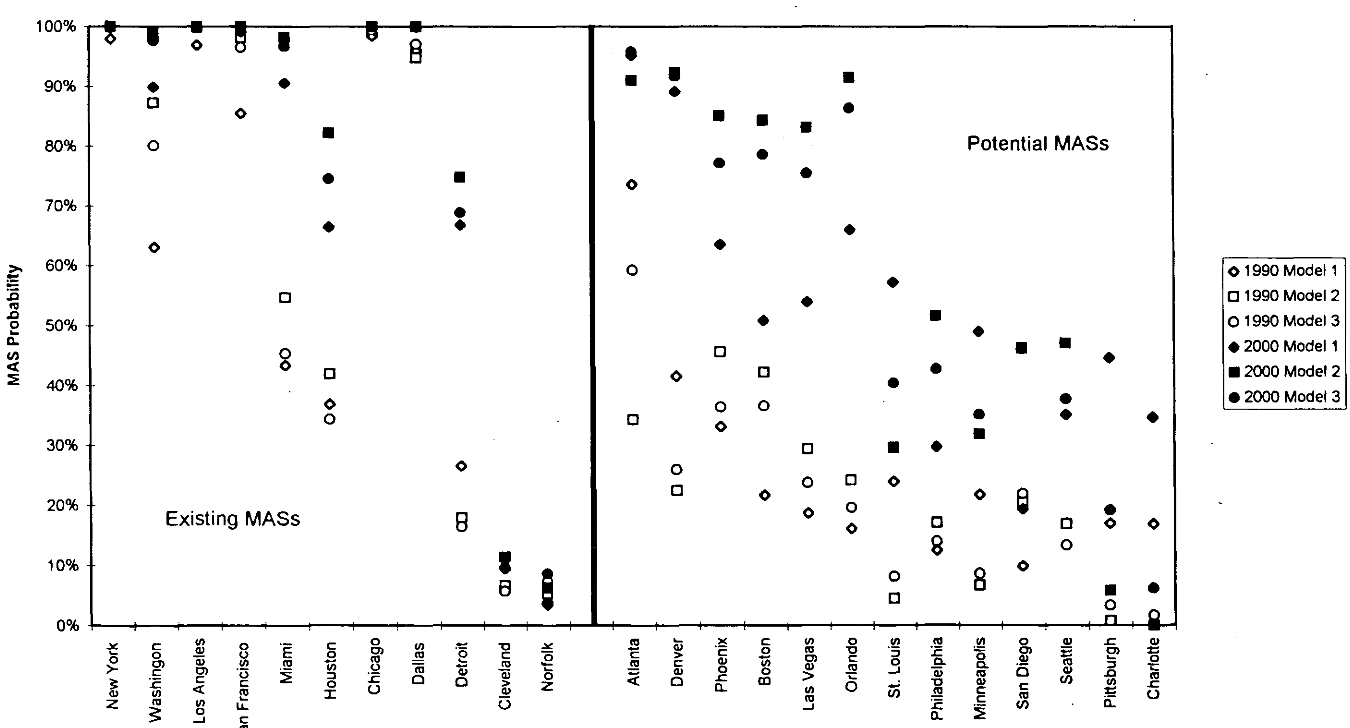


FIGURE 2 1990 and 2000 range of logit model predictions

folk are the least probable ones, based on their low traffic levels. These are all highly concentrated MASs. Both Cleveland and Norfolk are also cases in which the airports operate under separate local jurisdictions between which there is significant rivalry. This may help to explain why activity has not been consolidated at one airport in these regions. Among the SASs, Atlanta is the most likely candidate to be a MAS, based on 1990 data. Denver, Phoenix, Boston, and Las Vegas also have a fairly high MAS probability, although it is under 50 percent in all cases.

Figure 2 also shows MAS probability estimates for the year 2000, based on traffic growth projected by the FAA and assuming a ratio of enplanements to O&D traffic equal to that in 1990. The contrast with the 1990 results is striking. Six regions—Atlanta, Denver, Phoenix, Boston, Las Vegas, and Orlando—are forecast to realize traffic growth that would give them a MAS probability of over 50 percent based on two of the three models. Two others—St. Louis and Philadelphia—surpass the 50 percent threshold according to one of the models, whereas three other regions approach it. These results form the basis of the assertion made at the outset—conditions appear to be ripe for substantial increase in the number of multiple airport systems in the United States.

Figure 2 shows considerable variability in the MAS probabilities predicted by the different models. The major uncertainty behind this variability is whether the distribution of traffic between connecting and O&D passengers affects the probability of being a MAS. Regions with unusually high or low proportions of connecting traffic—St. Louis and Boston, for example—thus show the highest variability. Predictably, Model 1, which is based on enplanements only, yields the highest MAS probability for St. Louis, whereas the models that incorporate a connecting traffic effect yield the higher MAS probabilities for Boston.

Table 7 provides further indications of the potential for MAS development in the SAS regions included in Figure 2. It identifies those that are, or are forecast to be, subject to significant amounts of aircraft delay, and, using the concentration models discussed in Section 2, predicts what the enplanement and O&D traffic concentration levels would be if a MAS developed. (In applying the concentration models, we again assumed a ratio of enplanements to O&D traffic equal to that in 1990). With the exception of Las Vegas, airports in all these regions had significant amounts of aircraft delay in 1990. Consequently, additional capacity is likely to be needed. The predicted enplanement concentration gives an indication of how much traffic might be diverted from the existing airport if additional capacity were supplied in the form of a new airport (assuming the existing airport continued operating). Phoenix, Boston, Orlando, Las Vegas, Philadelphia, and San Diego have the lowest concentrations. In all of these cases, our model predicts a sizable (30 percent or more) diversion of enplanements from the existing airport under the MAS scenario. On the other hand, Atlanta, St. Louis, Minneapolis, Pittsburgh and Charlotte would be expected to have such a highly concentrated MAS that building an additional airport would hardly be worthwhile. Denver and Seattle are intermediate cases, in which MAS development would disperse traffic to some degree, although the primary airport would continue to be dominant. (Denver, of course, has elected to build a new airport but close the existing one.)

The predicted O&D traffic concentration measures the extent to which passengers originating in each hypothetical MAS region would have a real choice among airports, and also the degree to which having multiple airports would reduce the private and social costs of ground access. It is consistently lower than the enplanement concentration, suggesting that a MAS can yield sizable consumer choice and ground access benefits even when the overall traffic remains highly concentrated.

5. CONCLUSIONS

Our results suggest that the potential exists for multiple airport systems to play a significantly expanded role in the U.S. commercial airport system. We have identified 13 SAS regions whose traffic growth and traffic composition make them potential candidates for MAS development. Of these, roughly half could benefit substantially from such development in terms of traffic diversion, consumer choice, and ground access cost. All of these regions have commercial airports that have or are expected to soon have significant aircraft delay. Serious consideration should be given to expanding airport capacity in these regions by adding a second airport.

Deciding whether to build a second airport is bound to be controversial. Political conflict appears in the present era to be an

TABLE 7 Potential MAS Regions

Region	FAA Forecast Enplanements, 2000	Projected O&D Traffic, 2000	Over 20,000 Hours of Delay 1990	Over 20,000 Hours of Delay 2000	Range of Predicted MAS Statust Probabilities Min 2000	Range of Predicted MAS Statust Probabilities Max 2000	Predicted Concentration (HCI) if Region were MAS EPS	Predicted Concentration (HCI) if Region were MAS O&D Traffic
Atlanta, GA	24.6	8.7	X	X	90.7%	95.6%	0.86	0.78
Denver, CO	21.4	9.6	X		88.5%	92.1%	0.77	0.68
Phoenix, AZ	15.6	10.1	X	X	62.4%	84.7%	0.62	0.54
Boston, MA	13.7	11.0	X	X	49.6%	84.0%	0.48	0.43
Las Vegas, NV	14.1	10.4		X	52.8%	82.7%	0.55	0.48
Orlando, FL	13.9	9.9	X	X	48.0%	78.3%	0.56	0.49
St. Louis, MO	14.6	5.9	X	X	29.4%	56.0%	0.89	0.81
Philadelphia, PA	10.4	7.7	X	X	29.0%	51.2%	0.64	0.56
Minneapolis/St. Paul, MN	13.4	6.1	X	X	31.6%	47.9%	0.86	0.78
San Diego, CA	8.3	7.6	X	X	19.0%	46.0%	0.54	0.47
Seattle, WA	11.3	7.1	X	X	34.2%	46.7%	0.72	0.63
Pittsburgh, PA	12.8	4.3	X	X	5.8%	43.6%	0.94	0.89
Charlotte, NC	11.2	2.3	X	X	0.0%	33.8%	0.99	0.97

Source: Forecast EPS - Terminal Area Forecasts, FAA, CY1993.
Delays - Aviation System Capacity Plan, FAA, 1991/1992.

inevitable concomitant of any major addition to airport capacity. Savas (*11*) has observed that decisions involving urban systems frequently involve the search for a *single* politically feasible solution instead of choosing the best from a set of feasible alternatives. This clearly applies to airport planning. Our findings help establish the conditions under which a MAS may be viable, and thus when alternatives involving more than one airport can be added to the list of candidate solutions to be subjected to the political feasibility test. For example, it may be possible to build a more modest airport and keep the existing one operating instead of constructing a huge new airport and close the existing one, or avoid a major expansion of an existing airport in favor of adding capacity by means of a new airport. By no means will these MAS alternatives be the preferred ones in all situations, but in some cases they may allow capacity expansion to go forward when otherwise it would be politically infeasible.

If the near term benefit of MAS development is capacity expansion, in the long term there is also the potential of creating a competitive, entrepreneurial airport sector. In addition to permitting the obvious locational choices, this would encourage greater experimentation with services and prices, and thus increase the range of air travel options available to consumers. Put another way, airport deregulation is desirable for many of the same reasons that airline deregulation was. MASs, by curtailing the ability of airports to engage in monopolistic abuses, improve the prospects for such deregulation.

As Garrison and Gifford (*1*) point out, the air transportation system is in many respects mature, with highly standardized products and relatively little innovation. As air transport demand increases, the tendency is to respond by growth instead of development, by adding capacity to SASs instead of creating MASs. It is important to realize that this is not the only option, and that the MAS alternative could ultimately lead to a more innovative and dynamic air transportation system. We see an opportunity, and a challenge, in cultivating a competitive airport sector from monopolistic roots.

ACKNOWLEDGMENT

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Forecasting Air Travel Arrivals: Model Development and Application at the Honolulu International Airport

SANJAY KAWAD AND PANOS D. PREVEDOUROS

Honolulu International Airport is one of the dozen busiest airports in the United States. It provides a port of entry for foreign flights and both domestic and interisland terminals. For Hawaii's airport engineers and planners, this status makes short- to medium-term air travel forecasts essential, particularly for landside applications. A unique model system is described with separate models for each origin region or country. The models are estimated with the Cochrane-Orcutt regression procedure. Major explanatory variables include the gross national product (GNP), gross domestic product (GDP) (in various forms), and the consumer price index (CPI). Exchange rates, strength of currencies, and variables for wars, recessions, and airline strikes are also introduced. The models adhere closely to the actual number of arrivals, and all variables perform as expected. The USA model has an overall error rate (for the 18 years of the estimation span) of less than 0.05 percent and annual extreme errors ranging from −6.4 to 5.7 percent. The Japan model also has an overall error rate of less than 0.05 percent and annual extreme errors ranging from −7.5 to 10.4 percent. Near-future values for explanatory variables can be obtained from major economic organizations, thus the use of the model system requires only that planners update variable values annually from regularly issued publications. Long-term forecasts are more difficult due to the lack of published data. In those cases, the user must resort to a combination of trend extrapolation with ARIMA, as shown in this discussion, and educated estimates based on contemporary macroeconomic literature.

The development of an air travel demand model system for Hawaii is discussed. Hawaii's airport system includes five major and several secondary airports. It is owned by the state and managed by the Airports Division of the state department of transportation (DOT). The Honolulu International Airport is one of the busiest in the nation; in 1992, it ranked ninth in the number of domestic passengers and fourth in the number of international passenger arrivals (category X airports, American Airport Traffic Report 1993).

Because Hawaii's airport system is the primary mode of passenger transportation into and out of the state, accurate demand forecasting is essential. Forecasts are used for landside planning applications (e.g., ramp control, baggage handling, pedestrian corridor level-of-service, queueing analysis at check-in counters and security points, size of holding areas, parking demand, and traffic circulation volume) and by the Airports Division as input to its Airport Landside Planning System (ALPS) software.

The research goal was the estimation of user-friendly air travel forecasting models for the Airports Division. For ease of use and reliability of forecasts, the models were estimated with macroscopic data taken from the United Nations (UN), the Organization for Economic Cooperation and Development (OECD), the International Monetary Fund (IMF), the Economist Intelligence Unit (EIU), the Pacific Asia Travel Association (PATA), and World Bank publications. Variables representing other factors affecting travel behavior (e.g., wars, exchange rates, and promotional fares) also were introduced.

Two independent concepts for model estimation were established. The first entails the estimation of global air-travel generation and the estimation of Hawaii's (variable) share of that market. This process explicitly accounts for the effects of competition and is under consideration for future investigation. The second entails the estimation of separate forecasting models for each major originating point of air travel to Hawaii. Competition is accounted for in the number of arrivals from a particular country or region. Models for arrivals from the mainland United States and Japan are presented. Arrivals from these places of origin constitute approximately 75 percent of the total number of arrivals to Hawaii.

This study is unique in its consideration of economic, demographic, and other defining characteristics of the originating regions and countries. As noted in the literature review, such a model system has not yet been developed.

This study consists of five parts. After the introduction, a literature review focusing on forecasting methodologies and destination competition is presented. Concept development and methodology (including data description and variable definitions) are then discussed, followed by an explanation of the USA and Japan models with forecasts to the year 2000. The final section presents conclusions and directions for future research.

LITERATURE REVIEW

The review of literature that follows focuses on (a) air travel forecasting methodologies (estimation procedures and model specifications) and (b) the major explanatory variables that have been used in past studies and proven useful. The review also covers destination competition. Such a discussion is appropriate for destinations with a high number of tourist arrivals. [A more detailed presentation of existing literature can be found in a thesis by the first author (*1*)].

Forecasting Literature

Although several studies to model tourism in Hawaii have been undertaken (*2,3*), none estimate demand from originating countries based on the economic and demographic variables of those countries or the competition between tourist-attracting countries.

S. Kawad, Parsons Brinkerhoff Quade and Douglas, Inc., Two Waterfront Plaza, Suite 220, 500 Ala Moana Boulevard, Honolulu, Hawaii 96813. P. D. Prevedouros, Department of Civil Engineering, University of Hawaii at Manoa, 2540 Dole Street, Holmes Hall 383, Honolulu, Hawaii 96822.

The Hawaii Visitors Bureau (HVB), a nonprofit organization that promotes Hawaii as a tourist destination, forecasts visitor arrivals for the short-term (i.e., for a period of 1 year). HVB uses (a) survey data from a sample of travel agents worldwide, (b) immigration records, and (c) data from continuously conducted in-flight surveys. Data from the travel agents reflect committed (not future) travel plans, and the immigration and in-flight survey data offer insights concerning the actual situation of visitor arrivals.

The Department of Business, Economic Development, and Tourism (DBEDT) uses a model (*4*) to project visitor arrivals based on assumptions about factors such as air fares and income levels, which have failed to account for the (largely worldwide) economic recession of the early 1990s and the "air-fare wars" among airlines in recent years. The DBEDT model considers the economies of the U.S.A. and Japan markets only. Markets such as Korea, the Philippines, Australia, New Zealand, Canada, and Europe are also important to Hawaii, but are not considered in the DBEDT model. The main purpose of the DBEDT model is to forecast the state's economy and act as a source of information for land transportation models and highway planning.

Stuart (*5*) used the gravity model to interpret air-passenger traffic between Hawaii and the mainland United States. The aim of this study was to test the hypothesis that air-passenger traffic is a function of distance and population distribution. The model was not used to predict the future pattern of passenger movement to Hawaii.

A review of the literature reveals that much more work on aviation forecasting has been done outside Hawaii. The objective of the model specified by Crouch et al. (*6*) was to estimate the impact of international marketing activities of the Australian Tourist Commission (ATC) on the number of tourist arrivals. Multivariate log-linear regression analysis was used to estimate the elasticities of demand by considering the economies of the United States, Japan, New Zealand, the United Kingdom, and Germany. The model includes:

- Real per-capita disposable personal income (which is used as an approximate measure of the price of tourist services in Australia);
- Air fares to Australia from the origin country;
- Promotional expenditure by the ATC;
- A trend term to allow for changing "tastes"; and
- Dummy variables to account for the effect of special conditions in certain years.

The model reflects the historical data well, but its forecasting ability is questionable given the lack of knowledge for forecasting several of the independent variables.

Armstrong (*7*) used cross-section analysis and a logarithmic model form to forecast international tourism demand. Model variables include the number of tourist arrivals recorded in country *j* coming from country *i* (dependent variable), a value that is assumed to reflect the tourist appeal of country *j* and which arises from factors not explicitly included in the model. Those factors include:

- Climate;
- Resorts and culture;
- The population of country *i;*
- The income per capita of country *i* [gross national product (GNP) per capita];
- A value given to the proximity of frontiers or common language, if any, between countries *i* and *j;*
- The distance between generating country *i* and recipient country *j;* and
- The value of time for $n = 1963, 1967, 1975, 1980$.

It is not clear how the value of time is defined.

Two base years (1963 and 1967) were considered and the model gave tourist flows for the years 1975 and 1980 between each of the 522 pairs of generating and recipient countries. The forecasts were verified by conducting a time-series analysis of the actual number of tourists generated by each origin country as a function of its population, GNP per capita, and average distance traveled abroad. Armstrong concluded that the biggest increases over the forecast period 1967 to 1980 would be in arrivals to nontraditional tourist countries (namely, Fiji, New Zealand, Australia, etc.).

Witt and Martin (*8*) examined the choice of appropriate variables to represent tourists' cost of living for various origin-and-destination countries. The model was an attempt to test whether the consumer price index (CPI) is a suitable proxy for the cost of living of tourists at the destinations. Their model attempts to explain the flow of tourists from major origin countries [namely, France (to Portugal and the United Kingdom), Germany (to Austria and Italy), the United Kingdom (to Spain and Greece), and the United States (to Canada and France)]. A loglinear model structure was used. The lost of the time-series explanatory variables includes the population and personal disposable income of each origin country; the cost of living for tourists at each destination; a weighted average of the cost of tourism in substitute destinations; the exchange rate of the currencies between each origin-destination pair; air fares; a weighted average of air fares to substitute destinations; the cost of travel by surface; and dummy variables.

The authors concluded that tourist cost-of-living data were not superior to the simple CPI or simple exchange-rate proxies. The empirical results indicated that the CPI (either alone or with the exchange rate) is a reasonable proxy for the cost of tourism (*8*).

The literature shows that the GNP, CPI, and dummy variables representing airline strikes, recessions, and exchange rates are important determinants of intercity travel.

Destination Competition

Tourism is one of the most rapidly growing sectors of the international economy. As more countries realize the importance of tourism to their economies, the competition among them will increase. The U.S. market has a large share of the world tourism market and Hawaii's potential for growth in tourism is great.

In a study of the destinations competing with Hawaii (*9*), places with the same attributes (such as sun, sand, and sea) were chosen. Additional criteria were established to narrow the list. The Caribbean, Mexico, and Australia emerged as the primary destinations competing with Hawaii.

Studies also (*10–12*) have shown that natural beauty and climate are the primary elements that attract people to a destination. Additional factors include culture, sports, shopping, and night life.

Although the potential worth of attractiveness to modeling arrivals is obvious, the incorporation of such factors in time-series models is problematic for two reasons. First, definitions of attractiveness and historical measurements of it are lacking. Elements of attractiveness that remain constant over time (e.g., the cultural value of historical sights and major museums) are not useful in time-dependent models. Elements of attractiveness that change over time (e.g., crowding of beaches, congestion, and pollution) are useful in time-series models if (a) consistently measured over-time indices (or reasonable proxy variables) are available, and (b) future values for these indices can be forecast with reasonable confidence (i.e., easier to forecast than the dependent variable). There is a clear lack of research in this area, and to the best of the authors' knowledge, the aforementioned conditions are not met.

Second, the real issue may not be the actual quantitative assessment of a dimension of attractiveness (which could be estimated with a level of service or quality index), but its perception in various markets. Perceptions not only vary from reality, but also differ among cultural or ethnic groups. (One might ponder the perception of safety from crime in Los Angeles by Tokyo and New York City residents). Thus, perceptions add another layer of difficulty to an already difficult problem.

Because the goal of the research was to estimate a set of robust and user-friendly models for engineering and planning applications, and because of the issues discussed in this section, indices of attractiveness were not used.

METHODOLOGY

Model Structure

The initial modeling concept focused on the estimation of global air-travel generation, followed by the estimation of Hawaii's (variable) share of the international market. This process explicitly accounts for the effects of competition. The estimation of a global air-travel generation model is still at the conceptual level because the collection of global tourism data is difficult and good definitions of competing destinations are not available. Theoretically, all tourist destinations compete for visitors. The authors do not agree that only destinations with sun, sand, and sea, as concluded in the study conducted for the DBEDT by Arthur Young, Inc. (*9*), compete with Hawaii. Many Americans may decide to visit Europe instead of a seaside resort when the dollar is strong and the air fares to Europe are similar or less expensive than those for Hawaii. Besides the Caribbean, Mexico, and Australia (*9*), Florida and California are formidable competitors (particularly for families with children), not only because of lower total air fares, but also because of the abundance of family-oriented theme parks in those states. For similar reasons, other destinations in the Pacific (e.g., Indonesia, the Polynesian islands, Singapore, and Thailand) should be included when considering Asian markets. Thus, the problem of destination competition becomes complex and impossible to address with the scarce, often incompatible, and short-span time-series data available (n.b., properly adjusted and defined macroeconomic statistics are not available before the 1980s for several countries).

The actual approach for model development involved a model system with separate forecasting models for each major origin country (or region) of air travel to Hawaii. Competition is partly accounted for in the dependent variable, which is the number of arrivals from the particular country or region. It cannot be presumed, however, that preferences represented in the dependent variable will be perpetual. Hence, forecasts beyond a 5- to 10-year period should consider destination competition explicitly, or the models and their estimates should be updated regularly. (Specifically, the models were designed for forecasts up to 10 years and with the stipulation that the coefficients will be updated annually; hence continuously "corrected" forecasts can be obtained for sensible short- and medium-term planning applications).

Finding accurate time-series data of arrivals from a given region or country is a major challenge because the arrivals often include travelers who made a connection at the region. For example, most visitors to Hawaii from Hong Kong, Taiwan, Singapore, and China arrive via Tokyo. Therefore, sources that apply the appropriate screenings (from travel agent bookings and on-board surveys) were selected for the collection of arrival data. Specifically, arrival data from 1974 to 1983 were taken from PATA reports (*13*), and data from 1983 to 1992 were obtained from HVB publications.

The generic structure of the models is given as

$$ARRIVALS^i_N = ARRIVALS^i_{N-1} \cdot (1 + \%CHANGE^i_{N-1 \text{ to } N})$$

$$\%CHANGE^i_{N-1 \text{ to } N} = f(\text{GDP or GNP, CPI, CURRENCY EXCHANGE, STRIKE, WAR, AIR FARE, } \ldots)$$

where

$ARRIVALS^i_N$ = visitor arrivals in year *N*, for country or region *i*;
$ARRIVALS^i_{N-1}$ = visitor arrivals in year $N - 1$, for country or region *i*;
$\%CHANGE^i_{N-1 \text{ to } N}$ = model estimate of the percent change from year *N* to $N - 1$, for country or region *i*; and
$f(\text{GDP}, \ldots)$ = model specification (the list of explanatory variables in each model is presented later).

The following steps were part of the process of model development:

1. Data collection and selection of variables,
2. Estimation of alternative model specifications and statistical testing, and
3. Model refinement and selection.

Estimation Procedure

The equations were initially estimated using the ordinary least squares method. In all cases the Durbin-Watson (DW) statistic indicated the presence of autocorrelation; thus, the parameter estimates were inefficient and the regression assumptions were not valid. The models were reestimated using the Cochrane-Orcutt iterative procedure to reduce the likelihood of autocorrelation. The following criteria were used to arrive at the final models:

1. Correct signs for the coefficients: the GNP-GDP variable should have a positive sign, the CPI variable should have a negative sign, the exchange rate coefficient should be positive, and the dummy variables should have logical signs.
2. DW statistic: a DW statistic lying between 1.8 and 2.2 is used as a measure for no autocorrelation. A DW statistic equal to 2 indicates the absence of autocorrelation (*8*).
3. *t*-statistic and R^2 value: the statistical significance of parameter estimates and the ability of the model to explain a large portion of the variance of the dependent variable are important indicators of goodness-of-fit. However, models with the highest R^2 were not nec-

essarily selected as best if other criteria were violated. Also, variables with not-significant parameter estimates were retained when a reasonable justification was available.

Explanatory Variables

Several mostly macroeconomic variables were considered in the model specifications. Figure 1 presents several variables pertaining to the USA model. The dollar index of relative strength to a number of foreign currencies reported by the Chicago and New York currency markets (monthly futures) shows that, at times when the dollar is strong (e.g., 1984 and 1985), a decrease in arrivals is observed as foreign travel becomes more affordable. Conversely, when the dollar index dropped sharply in 1986, a sharp increase in arrivals to Hawaii was observed.

The annual change in arrivals and in the CPI show roughly opposite trends, as expected. Low inflation promotes discretionary expenditures such as vacations, whereas high inflation (e.g., 1978 to 1980) curtails them.

The annual change in arrivals and in the per-capita GDP show similar trends. A strong economy generates business and discretionary travel. Economic declines (e.g., 1987 to 1990) and recessions (e.g., 1981 and 1990) have a strong detrimental effect, which often lags by 1 year. For example, the poor economic performance in 1979 resulted in a decrease in arrivals in 1980.

Certainly, air travel is a multifaceted (multivariate) phenomenon; thus, a consistent correlation between arrivals and macroeconomic variables is not observed. As shown in the next section, however, the developed specifications (which include several of the aforementioned variables) result in a model that explains more than 75 percent of the variance of the dependent variable.

The list of variables used in the specifications of the USA model follows.

LLGDPC = Annual change of the gross domestic product per capita in percent; performed best in a logarithmic transformation and lagged. Specifically:

$$LLGDPC = 0.75 \cdot \text{Log}(GDPC_{N-1}) + 0.25 \cdot \text{Log}(GDPC_{N-2})$$

Thus, the per capita product of up to 2 years before the target year affects arrivals. The parameters of 0.75 and 0.25 were obtained with a trial-and-error process with values from 0 to 1. The combination shown yielded the best model fit.

CPI = Annual change of the consumer price index.

STRIKE = Dummy variable to account for the United Airlines strike in 1985; this event caused a significant drop in visitors to Hawaii given that United's approximate market share in Hawaii is 30 percent.

NATURE = Dummy variable to account for the devastation caused on Kauai by Hurricane Iniki.

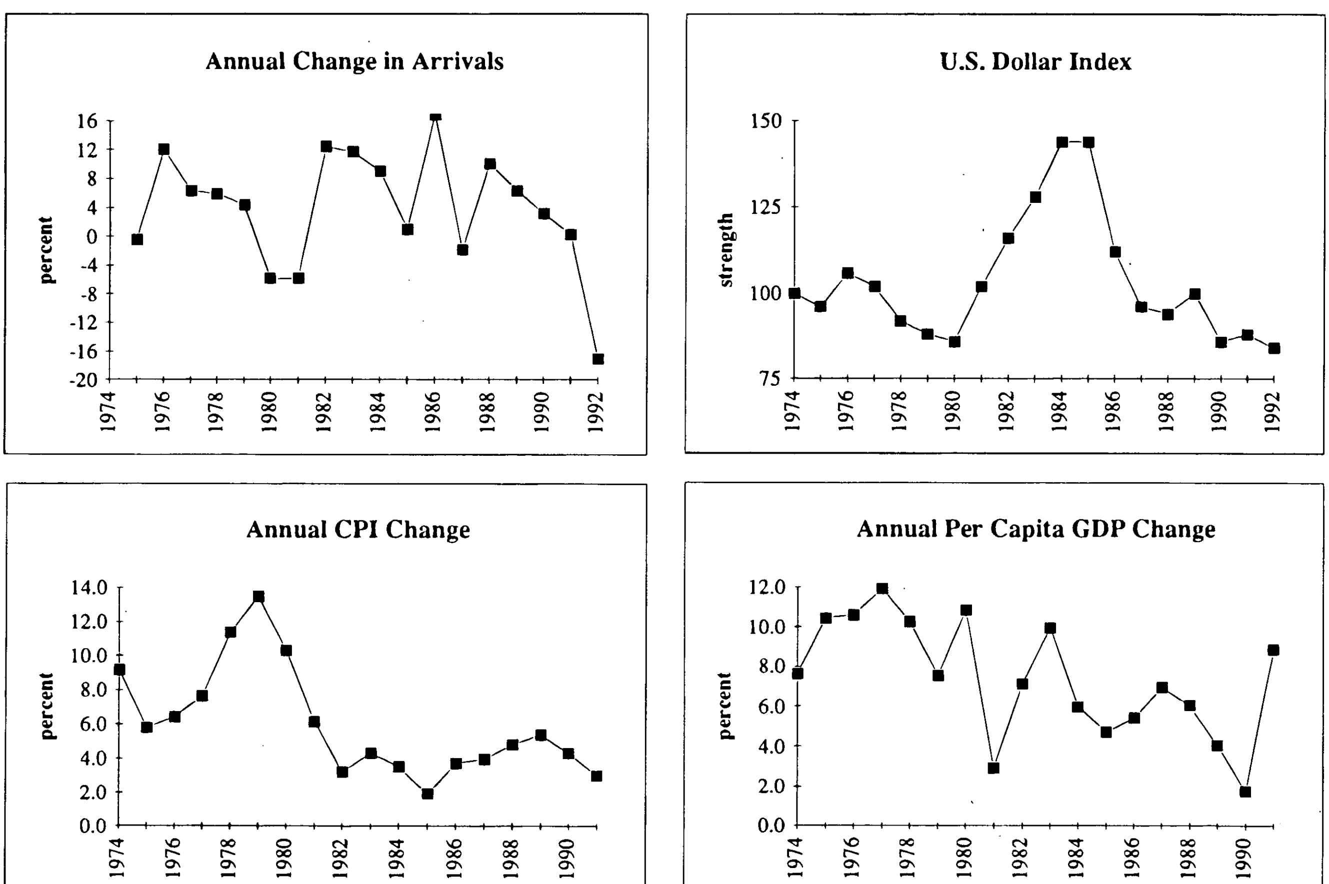

FIGURE 1 Trend of arrivals from the mainland United States and selected factors affecting them.

DJIA = Dummy variable based on the widely publicized Dow Jones Industrial Average index (DJIA) and used as a proxy of "economic mood." A positive economic (and spending) mood is assumed (value of +1) when the index gains 100 or more points within a year (difference between the last and first trading day for the year); a negative mood is assumed (value of −1) when the index loses 100 or more points in a year; and a neutral mood is assumed (value of 0) when the index gains or loses fewer than 100 points in a year. The use of this (and similar) indices may be particularly appropriate for high-cost destinations, which are afforded by mostly higher-income households, many of which are likely to be investors and, thus, will follow the economy's progress represented by the DJIA.

Variables tested but excluded from the final specification included:

1. The annual change in the gross state product (GSP) of the state of California. It was observed that when the annual growth of California's GSP drops below 3 percent, a decrease in arrivals is observed. California is a very important market for Hawaii, partly because of its market size, proximity, least-expensive air fares, and frequent service. Ultimately, a separate model for the West Coast is sought, but the procurement of arrival data that do not include stopovers in that region so far has not been possible.
2. The Persian Gulf war of 1991.
3. A dummy variable to account for years when the U.S. dollar is particularly strong (e.g., 1984 and 1985).
4. A variable based on Department of Commerce statistics on year-over-year change of disposable incomes in the United States.
5. A variable based on the average annual price of a barrel of crude oil.
6. Values of air fares, both current and constant, were used with little success, partly because air fare increases (and decreases in the early 1990s) follow the fluctuations in demand. In addition, the large proportion of frequent-flier seats used for travel to Hawaii further distorts the picture of air travel cost.

Figure 2 presents two major variables included in the Japan model and the dependent variable. The arrivals from Japan and the GNP show similar trends; for example, in the years of GNP decline (1983 and 1986), arrivals also decline. The only inconsistency in the two trends is the span between 1975 and 1979, when GNP growth declines but arrivals increase (partly because of the yen's strength). As a result, a dummy variable (J75–79) was introduced to account for the inconsistency, which can ultimately be explained by a lack of vacation time and the unlikelihood of foreign travel, both of which have changed substantially since the early 1980s, at least in Japan's urban centers.

The yen index serves as a signal to growth in arrivals from Japan. When a large gain in the exchange rate is observed, arrivals increase. Conceivably, large increases in the value of the yen vis-à-vis the dollar "make the news" in the Japanese market, which responds positively when an attractive product (a vacation or wedding in Hawaii) becomes more affordable in yen.

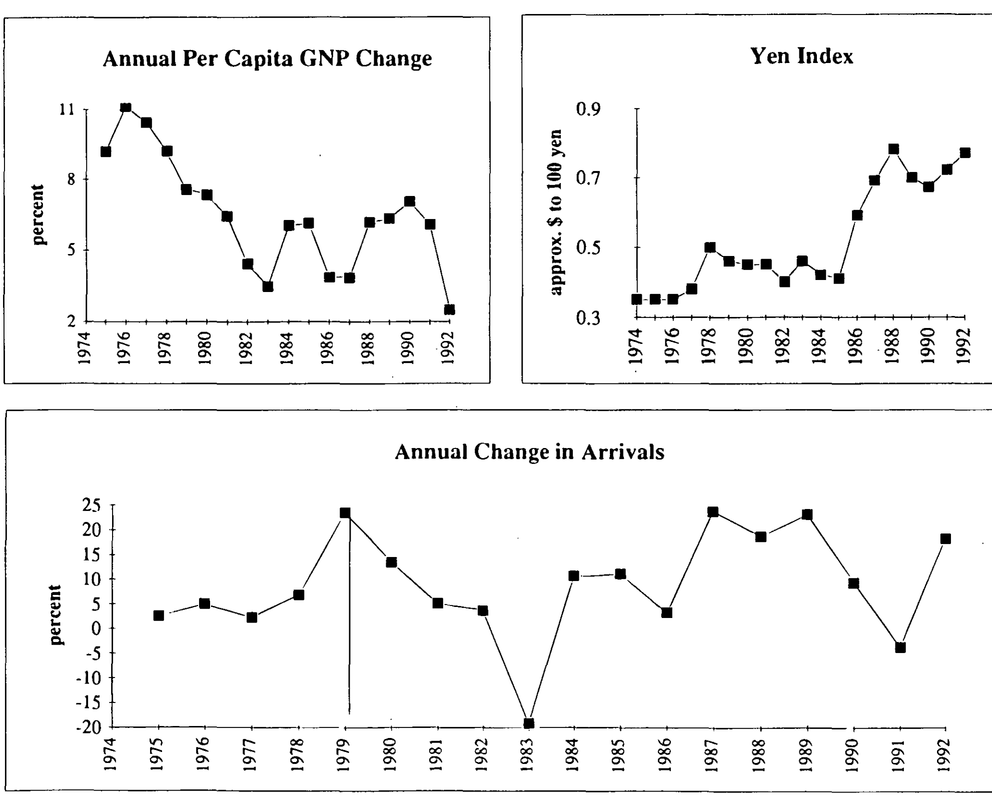

FIGURE 2 Trend of arrivals from Japan and selected factors affecting them.

The recent sharp recession in Japan tends to be confined to certain real estate and financial markets ("bubble, or overvalued economy") and has not affected the majority of the public. To the contrary, various economic reports suggest that falling prices and lowered inflation have made the recent recession a period of opportunity for most middle-class citizens of Japan.

The variables used in the specifications of the Japan model are:

LLGNPC = Annual change of the GNP in percent; performed best in a logarithmic transformation, and lagged for 1 year ($LLGNPC_{N-1}$).

YEN = Dummy variable to account for large increases in the strength of the ¥: 1 in 1979, 1987, 1988, 1989, and 1992, 0 for all other years (taken from historical futures charts of the Commodities Research Bureau); performed best when lagged for one year (e.g., the large increase in 1978 affects the 1979 arrivals due to advance bookings).

WAR = Dummy variable to account for the Persian Gulf war: 1 for 1991, 0 for all other years.

RECESSION = Dummy variable to account for the recessions in 1983 and 1991.

J75–79 = Dummy variable to account for the "cultural habit" of little vacation and foreign travel before the 1980s. For this period, contrary to logical expectations based on economic trends (see Figure 2), foreign travel from Japan was low and roughly constant, although Japan's economy was growing vigorously.

Variables tested but excluded from the final specification included:

1. The consumer price index at 1985 prices, and
2. The NIKKEI index (similar to the DJIA used for the USA market).

The fit was not successful partly because NIKKEI 225 index statistics before 1984 are not available.

MODEL ESTIMATION

The USA Model

The trend of arrivals shows that arrivals from the mainland United States increased for most years until 1991 (Figure 3, top). There was a slight decrease from the years 1979 to 1981. An economic recession in most parts of the country in late 1990 and early 1991 caused a sharp decrease from the mainland United States in 1992. Additional reasons for the decrease are the recession in California and the turbulence in the airline industry, which became a disincentive for travel to Hawaii because of the lowering of fares to most vacation destinations, excluding Hawaii (*14*). The final model estimated with the Cochrane-Orcutt procedure is shown in Equation 1.

	β *parameter*	*t-statistic*
$\%CHANGE^{USA}_{N-1\text{ to }N} =$	$-\ 8.50$	[1.23]
	$+30.82 \cdot LLGDPC$	[2.86]
	$-\ 2.17 \cdot CPI$	[4.61]
	$-16.09 \cdot STRIKE$	[3.54]
	$-12.64 \cdot NATURE$	[2.20]
	$+\ 4.00 \cdot DJIA$	[2.73]

$R^2 = 0.91$, adjusted $R^2 = 0.84$, $DW = 1.9$ (1)

All the variables are statistically significant at the 95 percent level (except for the intercept) and perform as expected. The GDPC has a positive impact on the arrivals whereas the CPI has a negative effect. The dummy variable for strike has a negative impact, the performance of the stock market has a positive impact, and the effects of Hurricane Iniki are negative, all as expected. The plot of the predicted arrivals corresponds with the actual arrivals. The Durbin-Watson statistic value of 1.9 indicates that autocorrelation is not a threat to the validity of this model. The standard error of estimate is 4.18, which is about half (51 percent) of the standard deviation of the dependent variable.

The Japan Model

The trend of arrivals shows that the arrivals from Japan increased moderately until the year 1986 (Figure 3, bottom). The years from 1986 onward display a steep increase except for 1991, which shows a decrease in the arrivals. The final model estimated with the Cochrane-Orcutt procedure is shown in Equation 2.

	β *parameter*	*t-statistic*
$\%CHANGE^{JAPAN}_{N-1\text{ to }N} =$	$-\ 4.28$	[0.46]
	$+13.65 \cdot LLGNPC$	[1.16]
	$+18.26 \cdot YEN$	[6.16]
	$-\ 7.87 \cdot WAR$	[1.28]
	$-15.36 \cdot RECESSION$	[3.37]
	$-\ 5.65 \cdot J75\text{–}79$	[1.18]

$R^2 = 0.87$, adjusted $R^2 = 0.78$, $DW = 2.0$ (2)

YEN and *RECESSION* are strongly significant, but the other variables demonstrate a significance at the 80 percent level only. All the variables perform as expected. It is evident that large fluctuations of the yen's strength affect the exchange rate accordingly, thus making foreign travel more (or less) attractive to visitors from Japan. The plot of the predicted arrivals corresponds with the actual arrivals. The Durbin-Watson statistic value of 2.03 indicates that autocorrelation is not a threat to the validity of this model. The standard error of estimate is 5.08, which is about half (54 percent) of the standard deviation of the dependent variable.

Based on the models' ability to reflect the historical arrival patterns, the following results summarize the estimation accuracy. The worst 1- and 5-year underestimates for the USA model were −6.4 and −2 percent, respectively. The worst 1- and 5-year overestimates for the USA model were +5.7 and +1.5 percent, respectively. The error for the total period between 1975 and 1992 was 0.046 percent. The worst 1- and 5-year underestimates for the Japan model were −7.5 and −1.2 percent, respectively. The worst 1- and 5-year overestimates for the Japan model were +10.4 and +2.8 percent, respectively. The error for the total period between 1975 and 1992 was 0.046 percent.

Forecasts

Forecast models 1 and 2 can be made in the following two ways.

1. Short-term predictions of arrivals can be done using data published by major organizations. Specifically, forecasts for the GDP and the CPI in the USA model can be input according to growth rates reported by the OECD (*15*) and the EIU (*16*). The GNP growth rates for the Japan model can be taken from the EIU. Population forecasts for most countries can be taken from the United Nations (*17*).

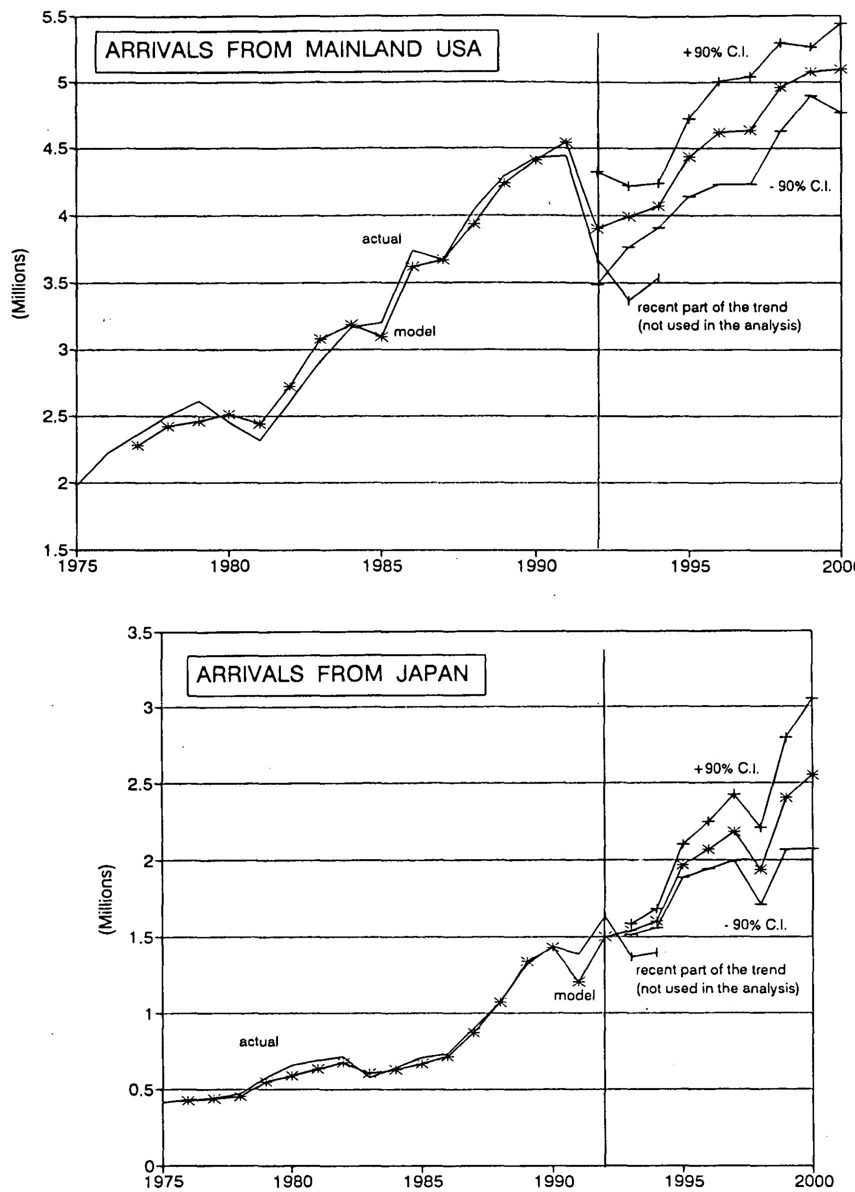

FIGURE 3 Actual arrivals, forecasts, and confidence intervals for two major origins of travel to Hawaii, the mainland United States (top), and Japan (bottom).

2. For longer-term forecasts, the user must resort to a combination of trend extrapolation with ARIMA and educated estimates based on contemporary macroeconomic literature basically because, beyond two years, macroeconomic forecasts are erratically documented and often unavailable. The forecasts presented in Figure 3 are based entirely on ARIMA applications. After extensive trial-and-error specifications, the best-fit ARIMA models were USA-GDP (1,1,0), USA-CPI (1,0,0), and Japan-GNP (1,0,0). Forecast values for the dummy variables were assigned so that the 1993-to-2000 average matches the 1975-to-1992 average.

ARIMA modeling enables the estimation of confidence intervals. The 90 percent-level confidence intervals are shown in Figure 3 for the forecast portion of the models. The recent trend of arrivals from the mainland United States and Japan (years 1993 and 1994) are also depicted in Figure 3. These values were not included in the model estimation process and are shown here for comparison.

The USA model could not account for the large decline in arrivals in 1993. A reversal of that drop in arrivals occurred last year and economic analysts expect travel to Hawaii to increase (*18*). Actual arrivals are expected to return to the rates depicted by the forecast.

The decline in arrivals, particularly in 1993, can be attributed partly to a drop in airline seating capacity (lift) from the mainland United States to Hawaii. Lift levels were approximately 7,600,000 in 1990, 7,200,000 in 1991, and 5,600,000 in 1993 (*18*). The corresponding load factors were 63 percent in 1990, 63.5 percent in 1991, and 67.5 percent in 1993. Although supply clearly exceeds demand, the increasing load factors and reduced number of scheduled flights in peak seasons are likely to cause seat reservation difficulties for potential visitors, and ultimately the abandonment of trips to Hawaii for those who have little time flexibility. A reason for the reduction of lift levels is given in the Bank of Hawaii's *Annual Economic Report* (*18*): "Much of the contraction of air service has arisen from airline concern with 1.2 billion mi of unredeemed frequent-flier claims. Not surprisingly, frequent fliers are more apt to redeem their miles on travel to Hawaii than they are on flights to the destinations on which the mileage was originally accumulated, so that Hawaii becomes an unprofitable destination for the carriers."

A notable narrowing of the confidence intervals appears for 1994 and 1999 in the USA model. The reason is that the GDP and CPI have opposite signs for those years and, by coincidence, the errors largely canceled each other.

The Japan model corresponds remarkably well with actual arrivals. However, the overall forecast may be somewhat optimistic. This is because the ARIMA forecast of the GNP assumes that the trend of a rapidly growing Japanese economy will continue. Reports in the financial press, however, state that Japan is less likely to sustain as rapid a growth as in the past due to tightening worldwide competition, the easing of trade barriers, and a partial loss of the pricing advantage on several durable products. Thus, the near-term forecasts for Japan should be based on published GNP forecasts, and the longer-term forecasts should be revised frequently.

CONCLUSIONS

The goal of the research was the development of a short- to medium-term econometric model system for forecasting air travel arrivals for the Hawaii DOT. The target use of the forecasts is landside planning applications. The model system is developed from readily available information, enabling the Airports Division to use it with no more effort than annual visits to the library to collect updated data. Models for the United States and Japan have been developed using the Cochrane-Orcutt regression estimation procedure. Similar models for Australia, Canada, Germany, Korea, New Zealand, and the United Kingdom were developed recently and are presented elsewhere (*19*).

Various diagnostic tests were conducted to arrive at the final models. All the explanatory variables perform as expected. The per-capita GDP (GNP for Japan) had a positive effect on arrivals, whereas the CPI had a negative effect. Large fluctuations of the yen's strength affect arrivals from Japan. The effect of the airline strike of 1985 was considerable. The effects of war (uncertainty, fear of terrorism, etc.) were shown to suppress foreign travel. The coefficient estimates reflect that the Persian Gulf war had a negative impact on arrivals from Japan. The USA model shows that arrivals also are sensitive to the trends in financial markets.

The models correspond remarkably well to the actual number of arrivals, and all independent variables perform as expected. The USA model has an overall error rate (for the 18 years of the estimation span) of less than 0.05 percent. Annual extreme values of error range from −6.4 to 5.7 percent. The Japan model also has an overall error rate of less than 0.05 percent. Annual extreme values of error range from −7.5 to 10.4 percent.

Potential improvements to these models would entail the consideration of other variables, such as the airline seat capacity to Hawaii and the tourist attractiveness of Hawaii (which may be declining as the state becomes more crowded, the hotels older, etc.). The model also can be estimated using monthly arrivals to account for seasonal effects.

ACKNOWLEDGMENT

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Flight Sequencing in Airport Hub Operations

CHING CHANG AND PAUL SCHONFELD

Airlines operating hub and spoke networks (HSNs) can reduce aircraft costs and passenger transfer times at hubs through efficient sequencing of flights. Typically, batches of flights are processed during relatively brief time "slots." When aircraft differ significantly in sizes or loads, there is a considerable potential for reducing the delay costs through efficient flight sequencing. Sequencing bigger aircraft last in and first out (BLIFO) minimizes the costs of aircraft delays, gate usage, and passenger time. Sequencing smaller aircraft first in and first out (SFIFO) maximizes the gate utilization and terminal capacity. Therefore, BLIFO is preferable when airports are not busy and gate utilization is unimportant. SFIFO is preferable when airports are very busy. Some intermediate sequences might also minimize total cost, depending on the relative costs of aircraft delays, gates, and passenger time. BLIFO or SFIFO, whichever is lower, provides a very good initial solution in most cases. A sequential pairwise exchange algorithm can then improve this initial sequence until no further improvement is possible.

Hub and spoke networks (HSNs) have been widely adopted by U.S. domestic airlines because they can greatly reduce the cost of connecting a given number of cities and improve the service frequency. When compared with direct flights, the main disadvantages of the HSN routing are additional transfer times and costs at the hub. To minimize transfer times and costs, a batch of aircraft has to arrive and depart within a short "time slot," and all aircraft should be on the ground simultaneously for at least a short period so that transfers can be made. The common ground time window (GTW) for passenger and baggage redistribution is the time between arrival of the last flight and departure of the first flight. The size of aircraft is related to passenger loads on different flights, especially for long-run scheduling purposes. Large aircraft imply expensive aircraft and large passenger loads. If the sequencing allows larger aircraft to spend less time at the hub, the costs associated with the flight sequencing will be reduced. For instance, later arrivals and earlier departures for the larger aircraft would reduce average passenger delay time and aircraft ground time cost. Thus, total transfer passenger delay and aircraft cost would be reduced if larger aircraft were the last in and first out.

Extreme sequences such as last in first out (LIFO), first in first out (FIFO), and their variants can be shown to minimize certain cost factors. Under certain traffic conditions or when certain cost factors dominate sequencing decisions, it can be shown that particular extreme sequences are optimal. In more complex cases, where no factor dominates and several factors must be traded off, sequencing solutions are also more complex. In such cases we will take the least cost extreme solution as an initial solution and use a sequential pairwise exchange algorithm to improve that initial sequence until no further improvement is possible.

C. Chang, Industrial Management Department, Chung-Hua Polytechnic Institute, Hsin Chu, Taiwan 30067, R.O.C. P. Schonfeld, Civil Engineering Department, University of Maryland, College Park, Md. 20742.

Our flight sequencing problem is to find a sequence that minimizes the total costs of passenger transfer delay, aircraft ground time, and gates. It is difficult to optimize exactly the sequence for a batch of N arrivals and N departures at a hub because there are $(N!)^2$ possible sequences. An efficient heuristic method to solve this flight sequencing problem is proposed in this report.

The literature on flight sequencing to minimize the costs of the passenger transfer delay, aircraft ground time, and gate use is scarce. Previous studies mostly focus on the Aircraft Sequencing Problem (ASP). In each of these ASP models (*1,2*), a static problem is considered, in which N aircraft are already present on holding stacks outside the terminal area. Each aircraft can land at any time, and the problem is to find the sequence that maximizes runway capacity (or utilization) or, alternatively, minimizes delays. Dear (*1*) examined the dynamic case of the ASP in which the composition of the set of aircraft varies over time. Psaraftis (*3*) developed a dynamic programming (DP) approach for sequencing N groups of aircraft landing at an airport to minimize total passenger delays. Dear and Sherif (*4*) examined the constrained position shifting methodology, with simulation from the perspectives of both pilots and air traffic controllers, and later (*5*) developed a computer system to assist the sequencing and scheduling of terminal area operations. Bianco et al. (*2*) proposed a combinatorial optimization approach to the ASP, in which maximizing the runway capacity or utilization was modeled as an n job (landing or takeoff) and one-machine (runway) scheduling problem with non-zero ready times. Venkatakrishnan et al. (*6*) developed a statistical model for the landing time intervals between successive aircraft using data from Logan Airport in Boston. They found that reordering the sequence of landing aircraft could substantially reduce the landing time intervals and thereby increase runway capacity. Considering stochastic aircraft arrivals, Hall and Chong (*7*) developed a model for scheduling flight arrivals and departures to minimize delays for passengers connecting between aircraft at a hub terminal.

A review of the aforementioned studies indicates that deterministic models for optimizing runway capacity or utilization have received considerable attention. However, it is also important to consider the costs of passenger transfer delay, aircraft ground time, and gate use at hub airports. In addition, departure sequences are interrelated with arrival sequences (for instance, due to minimum ground time constraints, and desirability of replacing departing aircraft with similarly sized arriving aircraft to improve gate utilization) and should be determined jointly. The flight sequencing problem considered here is to find the arrival and departure sequences at a hub that minimizes those three costs.

SYSTEM DEFINITIONS

A system of hub airports is defined as follows.

Route Network

An HSN that has one hub airport and N spoke city airports (Figure 1) is considered here. All spoke routes connect at the hub. To travel from one spoke city to another, passengers must transfer at the hub. Nonstop travel is possible only if the origin or destination is at the hub. A more general system would have multiple hubs.

Batch Arrivals and Batch Departures

A group of flights from various spoke cities arrive at the hub airport within a short time period, and then unload and load passengers and baggage during a common GTW; then, the same aircraft leave within a short departure period. If there are N arriving aircraft, there are also N departing aircraft.

Sequence

The sequence is the order of aircraft arrivals and departures. Two extreme sequences, FIFO and LIFO, are of special interest if aircraft are ranked by size or load. FIFO is the sequence in which aircraft depart in their order of arrival [Figure 2(*a*)]. LIFO is the sequence in which aircraft depart in their reverse arrival order [Figure 2(*b*)]. LIFO is interesting because it may allow larger aircraft and their passengers to arrive later and leave earlier, with considerable savings. FIFO is interesting because it can reduce slot durations. At busy airports in which gate utilization and terminal capacity are critical, a FIFO sequence can provide shorter intervals among successive batches of flights, as discussed later in this paper. Two extreme FIFO sequences are considered in which the aircraft order is by size. These are SFIFO, in which smaller aircraft are first, and BFIFO, in which bigger aircraft are first. Likewise, the LIFO options include SLIFO, in which smaller aircraft arrive last and depart first, and BLIFO, in which bigger aircraft arrive last and depart first.

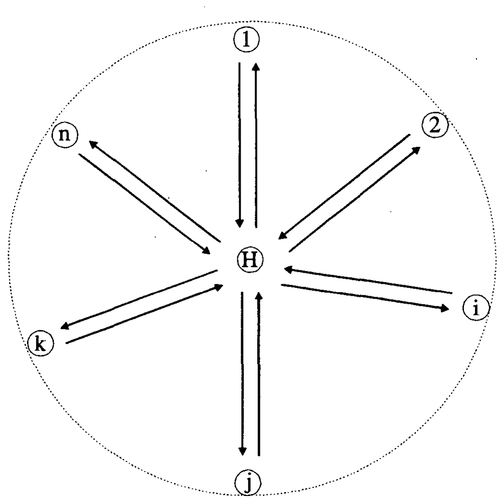


FIGURE 1 Hub and spoke network.

Cycle Time

The cycle time is the interval between the first arrival and the last departure in a batch of flights, along with the buffer separation time (Figure 3). The cycle time has four components:

1. The arrival period is the sum of all interarrival times, which is $\Sigma_{i=1}^{N-1} A_i$, where N is the total number of aircraft, and A_i is the interarrival time between the ith and $i + 1$st arrivals.
2. The GTW is the common time when all aircraft are simultaneously at the terminal, for transfer purposes. (However, transfer activities can start before the GTW and continue after its end.)
3. The departure period is the sum of all interdeparture times, which is $\Sigma_{i=1}^{N-1} D_i$, where D_i is the interdeparture time between the ith and $i + 1$st departures.
4. Buffer separation time, q, is the minimum separation time between successive slots, which is constrained by reliability considerations.

The first three time components are available for passengers, baggage, and cargo transfer activities. Aircraft are ready for departure after loading and servicing processes are completed.

Slot Sequences

Here, the time between the first aircraft arrivals of two consecutive batches is called a time slot. Figure 3(*a*) shows that if cycles do not overlap, the slot duration equals the cycle time. However, if cycles overlap [Figure 3(*b*)], the slot duration is smaller than the cycle time.

Figure 4 shows two types of slot sequences.

1. Overlapping cycles are possible if the departure sequence in the leading slot is similar to the arrival sequence in the trailing slot, as when:
   a. All slots are SFIFO or BFIFO [Figure 4(*a*)],
   b. Any pair of successive slots includes one SLIFO and BLIFO [Figure 4(*b*)].
2. Other nonoverlapping cycles can have
   a. Random sequences,
   b. Alternating SFIFO and BFIFO slots [Figure 4(*a*)],
   c. Similar LIFO sequences; that is, all SLIFO or all BLIFO slots [Figure 4(*a*)].

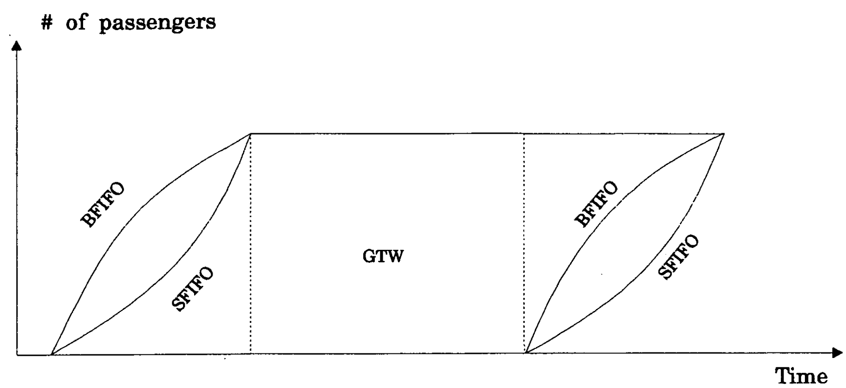
COST FUNCTIONS

Three cost components reflect the effects of different batch sequences. These are the total passenger transfer delay cost (C_p), the total aircraft ground time cost (C_a), and the total gate cost (C_g). Local passengers (originating or terminating at the hub) can be excluded in these total cost functions because there is no difference between HSN routing and direct flights. All these costs are computed in the same units ($/slot). The total relevant cost function is

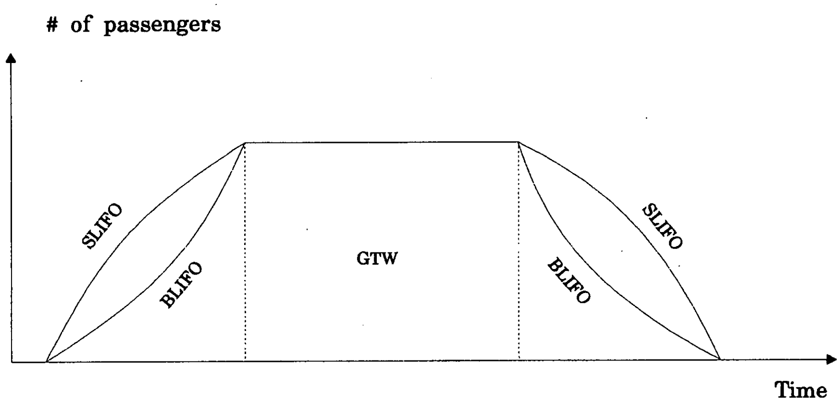
$$C = C_p + C_a + C_g \quad (1)$$

where C = total cost per slot for the hub operation ($/slot).

We define these three component costs as follows.



(a) FIFO Sequence



(b) LIFO Sequence

FIGURE 2 FIFO and LIFO sequences.

a. The passenger transfer delay is incurred by redistributing transfer passengers and their baggage from their original aircraft to their destination aircraft at the hub. The delay for each passenger is the difference between the passenger's departure time from the hub and the passenger's arrival time at the hub. Therefore, the total passenger transfer delay cost is the sum of delay costs for all transfer passengers in a batch of arrival and departure flights

$$C_p = V_p\left(\sum_{i=1}^{N}\sum_{j=1}^{N} P_{ij}\, t_{ij}\right) \quad (2)$$

where

- C_p = total passenger transfer delay cost per slot ($/slot),
- v_p = time value of transfer passengers ($/passenger hour),
- P_{ij} = number of transfer passengers from arrival aircraft i to departure aircraft j (passengers), and
- t_{ij} = the transfer delay time from arrival aircraft i to departure aircraft j (hours/slot).

b. The aircraft ground time is the time that an aircraft dwells at the hub. For HSNs, a batch of aircraft arrive and depart within a slot and all aircraft are on the ground simultaneously for at least a short period so that transfers can be made. An aircraft's ground time is determined by its arriving and departing times. The total aircraft ground time cost is the sum of ground time cost for all aircraft

$$C_a = \sum_{i=1}^{N} a_i\, v_{ai} \quad (3)$$

where

- C_a = total ground time cost for all aircraft in a slot ($/slot),
- a_i = the time aircraft i is on the ground (hours/slot), and
- v_{ai} = ground time value of aircraft i ($/hour).

c. The total gate cost includes the hourly gate fixed cost and hourly gate usage cost. The fixed cost accounts for the gate construction and equipment installation. The usage cost is incurred when an aircraft parks and uses a gate. Because gates can have different characteristics in the same terminal, the gate fixed cost depends on the gate size and slot duration, and the gate usage cost depends on gate size and gate occupancy time

$$C_g = \sum_{i=1}^{N} (v_{ci}\, t_{gi} + v_{oi}\, t_{oi}) \quad (4)$$

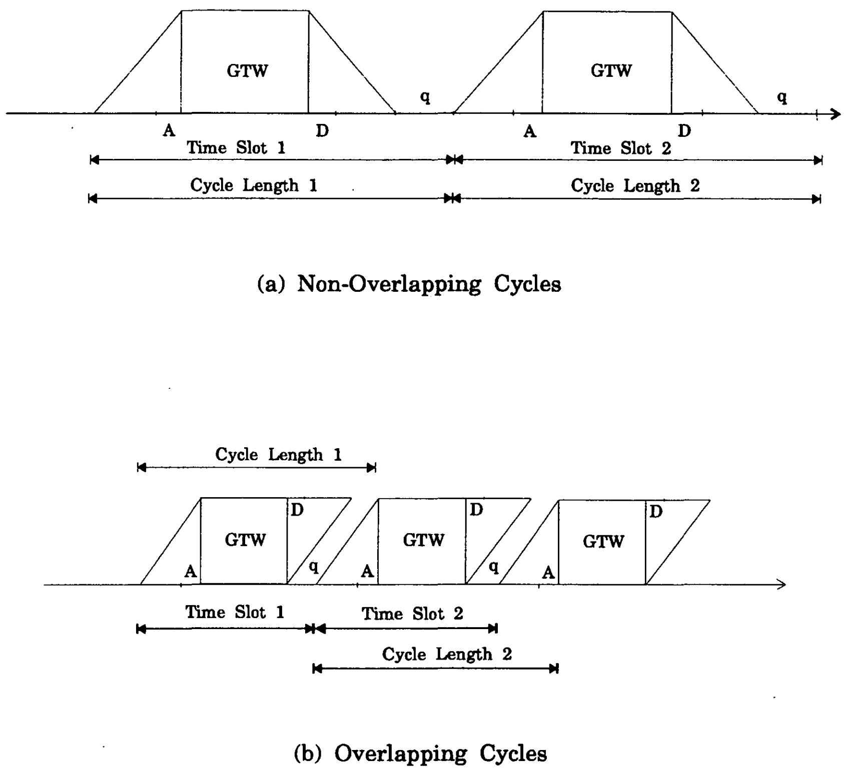


FIGURE 3 Overlapping and nonoverlapping cycles.

where

C_g = total gate cost per slot (\$/slot),
v_{ci} = fixed cost of gate i (\$/hour),
v_{oi} = usage cost of gate i (\$/hour),
t_{oi} = gate i's occupancy time (hours/slot), and
t_{gi} = slot duration (hours/slot).

CONSTANT SLOT DURATION

A simplified case with constant slot duration is considered first, on the basis of these assumptions:

1. All transfer passengers considered arrive and depart within the same slot, and all transfer activities are completed within that slot.

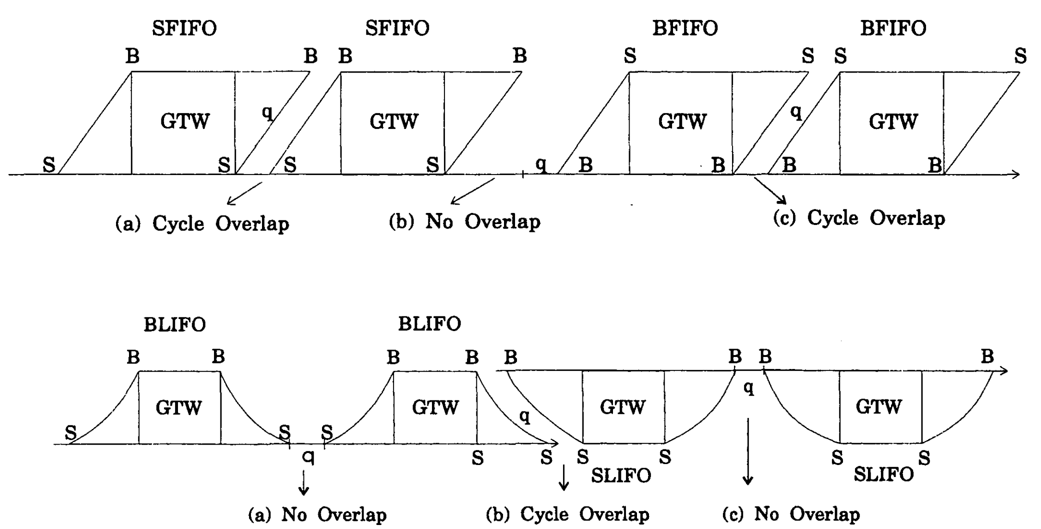


FIGURE 4 (*a*) Possible FIFO sequences; (*b*) LIFO sequences.

2. The number of gates, G, is greater than or equal to the number of aircraft, N.
3. The ground time window (T) is a constant.
4. Aircraft arrive punctually.

No other scheduling constraints limiting flight arrival and departure times should be considered in this problem. The ground activities of an aircraft include unloading passengers, baggage, and cargo; and cleaning, refueling, and loading passengers, baggage, and cargo. A, D, and T are fixed quantities and are assumed in this case to be independent of the sizes of aircraft. The buffer separation time between two time slots is q. Therefore, the slot duration is constant.

Analysis of Sequences

We first explore the extreme sequences LIFO and FIFO to determine in what situations they actually yield optimal solutions and then consider how more complex cases can be solved.

LIFO Sequence

In the LIFO sequence aircraft depart in their reverse order of arrival. Thus, a LIFO sequence benefits later arrivals and makes earlier arrivals a disadvantage. If larger aircraft (with higher costs per aircraft hour and passenger loads) are required to arrive later than smaller aircraft, such a BLIFO sequence minimizes the total passenger transfer delay cost, aircraft ground time cost, and gate usage cost. Figure 5 shows how BLIFO minimizes the total passenger transfer delay cost; the abscissa is time, and the ordinate is the cumulative number of passengers. The areas covered by the arrival curve, the (GTW), and departure curve in Figure 5 represent the total passenger transfer delay. Because the GTW has a fixed value, we only need to consider the areas covered by the arrival and departure curves. The slopes of arrival or departure curves represent the number of arriving or departing passengers per time unit; that is, the passenger departure rate. It can be observed in Figure 5 that the area under the BLIFO arrival and departure curves is smaller than areas for any other sequences. Thus, BLIFO minimizes the total passenger transfer delay cost. To minimize the total passenger transfer delay, aircraft should arrive in ascending order of their passenger arrival rates (the number of arriving passengers/runway time unit) and depart in descending order of their passenger departure rates.

Because larger aircraft may need more ground time than smaller ones, the BLIFO departure sequence must be modified to consider which aircraft are actually ready to leave. Smaller aircraft that are ready early need not wait for the unready larger aircraft. Accordingly, the aircraft departure sequence can be modified as follows.

Step 1. Check all aircraft to find which ones are ready to leave.

Step 2. Sort all ready aircraft in descending order of their passenger departure rates, and let the aircraft with the largest passenger departure rate leave.

Step 3. Check the unready aircraft. If new aircraft become ready to leave, let them join the list of ready aircraft. Go to Step 2.

The way in which BLIFO minimizes total aircraft ground time cost can also be explained graphically. An aircraft's dwell time is the interval between its arrival time and departure time. Figure 5 shows that with BLIFO, larger aircraft have smaller dwell times. Since for BLIFO $a_1 \leq a_2 \leq \ldots \leq a_N$ and $v_{a1} \geq v_{a2} \geq \ldots \geq v_{aN}$, where a_i is the ith largest aircraft dwell time and v_{ai} is the ith largest aircraft's time value, BLIFO minimizes the total aircraft ground time cost (Equation 3).

A similar argument can be used to show that BLIFO minimizes total gate usage cost since in Equations 3 and 4 the total gate usage cost function has the same structure as the total aircraft ground time cost function. Consequently, BLIFO minimizes total passenger transfer delay cost, total aircraft ground cost, and total gate usage cost, but not the total fixed cost of gates.

FIFO Sequence

When gates differ in size and cannot all accommodate the largest aircraft, the sequence of flights depends on the order in which gates of different sizes become available after handling the previous batch of aircraft. With the gate-aircraft size compatibility restriction, a BLIFO slot cannot closely follow a preceding BLIFO slot. This reduces the gate utilization and terminal capacity, which are very

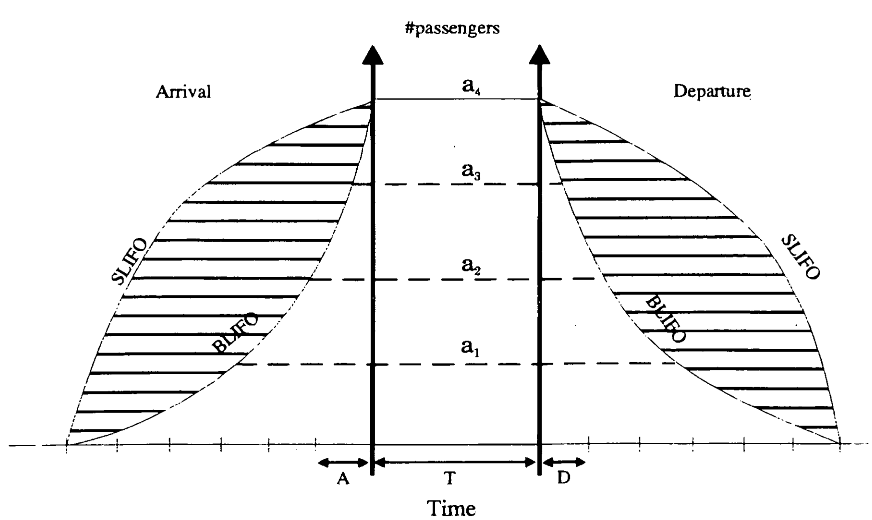


FIGURE 5 BLIFO and SLIFO sequences.

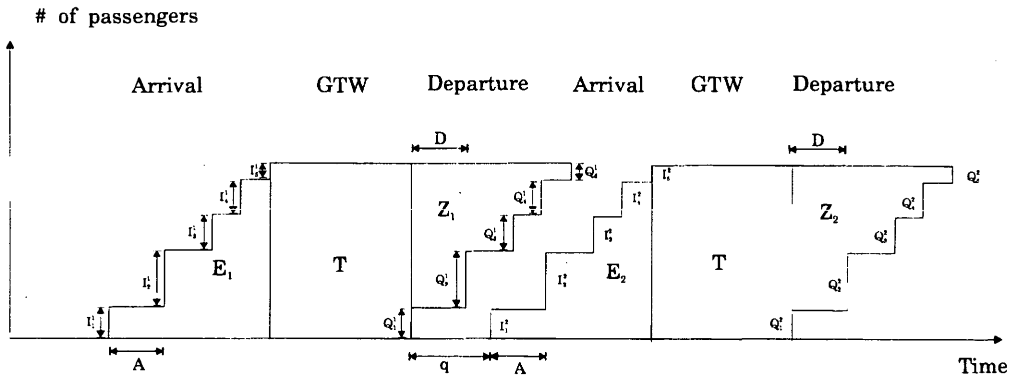


FIGURE 6 Overlapping slot sequences.

important at busy airports. To maximize the gate utilization and terminal capacity, the slots must overlap tightly. Two succeeding slots can overlap tightly if the departure sequence in the leading slot is similar to the arrival sequence in the trailing slot (Figure 6). FIFO yields tightly overlapping sequences for successive slots when the departure sequence in the earlier slot is the same as the arrival sequence in the later slot. Thus, FIFO can increase gate utilization and terminal capacity. Two extreme cases of FIFO, namely SFIFO and BFIFO, significantly affect the total passenger transfer delay when slots must overlap tightly. To minimize the total passenger transfer delay, the areas of Z_t and E_t in Figure 6, where t is the slot number, should be minimized. When interarrival times (A) and interdeparture times (D) have fixed values, the least transfer delay sequence minimizes areas $(E_1 + Z_1)$ in Figure 6, where $t = 1$. For instance, assume that there are five aircraft in each slot in Figure 6. Equation 7 represents the total passenger transfer delay. In minimizing total delay, subject to the overlapping slot constraint, the following results are obtained:

$$Area\ E_t = 4AI_1^t + 3AI_2^t + 2AI_3^t + AI_4^t \tag{5}$$

$$Area\ Z_t = DQ_2^t + 2DQ_3^t + 3DQ_4^t + 4DQ_5^t \tag{6}$$

$$Min\ Area\ (E_t + Z_t) = 4AI_1^t + (3AI_2^t + DQ_2^t) + 2AI_3^t + 2DQ_3^t) + AI_4^t + 3DQ_4^t) + 4DQ_5^t \tag{7}$$

where

I_m^t = the total number of transfer passengers on the mth arrival aircraft in slot t, and

Q_m^t = the total number of transfer passengers on the mth departure aircraft in slot t.

If $I_m^t \approx Q_m^t$ (the number of the transfers on mth arrival aircraft is similar to the number of the transfers on the mth departure aircraft), for all m, the following is true:

a. If $A > D \Rightarrow \{I_1^t < I_2^t < I_3^t < I_4^t < I_5^t\}$ and $\{Q_1^t < Q_2^t < Q_3^t < Q_4^t < Q_5^t\}$ minimizes areas of $(E_t + Z_t)$. This sequence is SFIFO.

b. If $A < D \Rightarrow \{I_1^t > I_2^t > I_3^t > I_4^t > I_5^t\}$ and $\{Q_1^t > Q_2^t > Q_3^t > Q_4^t > Q_5^t\}$ minimizes areas of $(E_t + Z_t)$. This sequence is BFIFO.

c. If $A = D \Rightarrow$ all FIFO sequences have the same transfer delay.

Accordingly, either the SFIFO or BFIFO flight sequence minimizes total passenger transfer delay when slots must overlap tightly and $I_m^t \approx Q_m^t$, for all m. However, if $I_m^t \not\approx Q_m^t$, for all m, neither SFIFO nor BFIFO guarantees the minimum total passenger transfer delay.

Similarly, it is easy to find a sequence that minimizes total aircraft ground cost and gate usage cost since both costs are related to aircraft sizes and their dwell times. Figure 6 shows that the following properties are true when slots must overlap tightly. (It should be noted that here I_m^t need not be equal to Q_m^t, for all m, since both costs are not related to the passenger loads.):

d. If $A > D$, SFIFO minimizes total aircraft ground time cost and total gate usage cost.

e. If $A < D$, BFIFO minimizes total aircraft ground time cost and total gate usage cost.

f. If $A = D$, all FIFO sequences have the same total aircraft ground time costs and total gate usage costs.

For this simple case when slots must overlap tightly, either SFIFO or BFIFO minimizes total aircraft ground time cost and gate usage cost.

When slots overlap tightly and $I_m^t \approx Q_m^t$, for all m, the least total cost sequence is:

g. SFIFO, if $A > D$.

h. BFIFO, if $A < D$.

i. All FIFO sequences have the same total costs, if $A = D$.

If $I_m^t \not\approx Q_m^t$, for all m, the above results may not be true. However, (*d*), (*e*), and (*f*) are still true when slots must overlap tightly. If neither SFIFO nor BFIFO minimizes total passenger transfer delay, the sequence which minimizes total passenger transfer delay has higher total costs of aircraft ground time and gate usage. Therefore, the total cost of SFIFO, if $A > D$, or BFIFO if $A < D$, is very close to the minimum total cost when slots must overlap tightly (*8*).

3.2. Preferable Sequence

When an airport is not busy and the gate utilization (gate fixed cost) can be ignored, BLIFO is preferable because it minimizes the total passenger transfer delay, aircraft ground time, and gate usage cost. If aircraft are not ready to leave as soon as BLIFO sequence requires, the BLIFO departure sequence should be modified as in the LIFO sequence already described.

When an airport is very busy and slots must overlap tightly, a FIFO sequence (specifically SFIFO if $A > D$ and BFIFO otherwise) maximizes gate utilization as well as terminal capacity and is the least total cost sequence if $I'_m \approx Q'_m$, for all m. When $I'_m \not\approx Q'_m$, for all m, neither SFIFO nor BFIFO may be the least total cost overlapping sequence. However, either SFIFO or BFIFO is still preferable because the total cost of SFIFO or BFIFO is very close to the minimum total cost.

When an airport's condition is moderately busy, trade-offs among passenger time, aircraft costs, and gate cost may lead to a least total cost sequence in between extreme sequences such as BLIFO, BFIFO, or SFIFO. Moreover, the time values of passengers, aircraft, and gates vary in different times and places. In such cases, the least total cost sequence may be found by starting from some initial solution and using the sequential pairwise exchange algorithm to try swapping aircraft positions in the sequence until no further improvement is possible. We can choose the best extreme solution (i.e., BLIFO or SFIFO if $A > D$ and BFIFO otherwise) as our initial solution and then improve it with a systematic exchange algorithm. The total number of exchanges is $N(N - 1)/2$, where N is the total number of aircraft, for example, [1,2], [1,3], . . . , [1,N], [2,3], [2,4], . . . , [N − 2,N − 1], [N − 2,N], [N − 1,N]. For instance, assume that $A > D$. Our sequential pairwise exchange algorithm to improve the flight sequencing is as follows.

Step 1. Compute the total costs of SFIFO and BLIFO. The one with the lower total cost is the initial solution. Store its total cost.

Step 2. Sequentially choose a pair of aircraft and exchange their arrival orders. Compute the new total cost.

Step 3. If the new total cost is below the previous one, substitute it and store the new arrival sequence. Otherwise, keep the previous sequence. Go to Step 2.

This algorithm was used by Chang (*8*) and had a reasonable computation time.

VARIABLE SLOT DURATION

When the interarrival and interdeparture times are variable and the GTW is constant, slot duration differs for various flight sequences. If an airline accounts for a significant fraction of the flights at an airport, the runway capacity directly affects the interarrival and interdeparture times of an airline's batch of connecting flights. One key factor that can affect the interarrival and interdeparture times is the minimum separation required by FAA to guard against wake-vortex turbulence (*9*). The wake-vortex separation depends on weights of the leading and following aircraft. Three weight classes of aircraft (heavy, large, and small) must be considered.

Minimum Separation Requirement

Let A_{ij} be the interarrival time between two successive landing aircraft i and j, and D_{ij} be the interdeparture time between two successive take-off aircraft i and j, where both i and j are aircraft size indices. Aircraft are ordered and labeled according to decreasing size; for example, {1, 2, 3, 4} are heavy aircraft, {5, 6, 7, . . . , 10} are large aircraft, and {11, 12, . . . , N} are small aircraft. Let the time period between the first arrival and the last arrival be called total arrival time, and the time period between the first departure and last departure be called total departure time. Based on the FAA's minimum separation regulation, the following properties exist:

a. $A_{ij} \leq A_{ji}$, if $i \geq j$,
b. $D_{ij} \leq D_{ji}$, if $i \geq j$,
c. $A_{ij} \geq D_{ij}$, for all ij pairs.

Overlapping Sequence

In order to maximize the gate utilization and terminal capacity, slots should overlap tightly. When interarrival times and interdeparture times are dependent on the relative weight classes of two successive landing and takeoff aircraft, FIFO can still increase the gate utilization. Assume that departure processes are fixed. Based on these properties, if aircraft arrive in the order of {Small, Large, and Heavy}, the minimum total arrival time is obtained. Due to property (*a*), A_{ij} would be smaller than A_{ji} if $i \geq j$. In order to minimize total arrival time, small aircraft should land before large aircraft. Similarly, for a fixed arrival process, in order to minimize total departure time, smaller aircraft should take off before larger aircraft. Accordingly, SFIFO minimizes cycle length and slot duration since SFIFO has the smallest total arrival and departure times. Therefore, when slots must overlap tightly, SFIFO is the overlapping slot sequence that maximizes the gate utilization and terminal capacity.

Because the interdeparture time is slightly shorter than the interarrival time, SFIFO benefits larger aircraft. This implies that SFIFO is the overlapping sequence that minimizes the total cost of aircraft ground time.

SFIFO has the smallest gate time and can minimize total gate fixed cost because the shortest slot duration sequence yields the highest gate utilization. In addition, SFIFO minimizes the total aircraft ground time. Therefore, SFIFO also minimizes total gate usage cost. Consequently, SFIFO is the overlapping sequence with the least total gate cost.

On the basis of the results of the constant slot duration case, if interarrival time, A_{ij}, is greater than interdeparture time, D_{ij}, for all i and j, and $I'_m \approx Q'_m$ (the number of the transfers on mth arrival aircraft is similar to the number of the transfers on the mth departure aircraft), for all m, SFIFO is the overlapping sequence with the least total passenger transfer delay.

With SFIFO, similarly sized aircraft arrive or depart together, consistent with the principle of grouping takeoffs and landings of similarly sized aircraft (*6*). Similarly sized aircraft land or take off together and average interarrival time and interdeparture time are minimized. Therefore, SFIFO maximizes runway capacity in such hub operations.

Thus, SFIFO is the least total cost overlapping sequence if $I'_m \approx Q'_m$, for all m. Otherwise, SFIFO may not minimize total passenger transfer delay. The SFIFO Sequence section of this paper also indicates that the total passenger transfer delay of SFIFO is close to the optimal value. Moreover, SFIFO still minimizes total aircraft ground time cost and total gate cost (including gate usage and gate fixed costs) when slots must overlap tightly. Thus, SFIFO is a near-optimal overlapping sequence because its total cost is close to the minimum total cost when slots must overlap tightly.

4.3. Nonoverlapping Sequence

When an airport is not busy and gate utilization is unimportant, BLIFO is still preferable. BLIFO is the sequence in which aircraft arrive in ascending order of their passenger arrival rates (the number of arriving passengers per runway time unit) and depart in descending order of their passenger departure rates. This always benefits large aircraft and reduces total cost significantly. However, BLIFO may have a longer slot duration than SFIFO. The total interarrival time for BLIFO is the same as that for SFIFO, but the total interdeparture time for BLIFO is greater than that for SFIFO. For instance, assume {1, 2, 3,4} are heavy aircraft, {5, 6, 7, 8} are large aircraft, and {9, 10} are small aircraft. Let the departure sequence of SFIFO be (10, 9, 8, 7, 6, 5, 4, 3, 2, 1). The departure sequence of BLIFO is (1, 2, 3, 4, 5, 6, 7, 8, 9, 10). Therefore, the difference of the slot durations between BLIFO and SFIFO is the difference of the separations, that is, $\sigma_{i=1}^{9} (D_{i,i+1} - D_{i+1,i}) = D_{45} - D_{54} + D_{89} - D_{98}$, divided by the take-off speed. Other interdeparture times are the same (e.g., $D_{12} = D_{21}$) since interdeparture times for SFIFO and BLIFO are equal if two successive takeoff aircraft are in the same weight class. For instance, if all aircraft are in the same weight class, BLIFO and SFIFO have the same slot duration. Since FAA defines only three weight classes and BLIFO is also consistent with the principle of grouping landings or takeoffs of similarly sized aircraft, the difference in total departure times between SFIFO and BLIFO is small. This difference can be ignored if the number of aircraft in a slot is large. BLIFO has a very small cycle time. The arguments used in the section LIFO Sequence can also be used to show that BLIFO with variable interarrival and interdeparture times minimizes the costs of total passenger transfer delay, total aircraft ground time, and total gate usage. The BLIFO departure sequence can again be modified to deal with unready flights with the procedures described in the LIFO Sequence section.

CONCLUSIONS

The flight-sequencing problem considered here is to seek an efficient flight sequence that minimizes the total costs of passenger transfer delay, total aircraft ground time, and gates. When aircraft differ significantly in size or load, there is considerable potential for reducing the costs through efficient flight sequencing. In addition, aircraft landings and takeoffs must satisfy the minimum separation requirement. The interarrival times and interdeparture times depend on the weight classes of two successive aircraft landings or takeoffs. The flight-sequencing disciplines that favor large aircraft such as SFIFO and BLIFO may minimize the considered total cost under some circumstances. Even if SFIFO or BLIFO does not minimize the total cost, one of them (the one with the lower total cost) will be a good initial solution for the flight sequence, which can then be improved with the sequential pairwise exchange algorithm.

When an airport is not busy, the gate utilization is less important and gate-fixed cost can be neglected. BLIFO is then preferable since it minimizes the costs of total passenger transfer delay, total aircraft ground time, and total gate usage. When an airport becomes busy, the gate utilization and terminal capacity become more critical and slots should overlap tightly. SFIFO is the least total cost overlapping sequence if $I_m' \approx Q_m'$, for all m. However, if $I_m' \not\approx Q_m'$, for all m, then SFIFO may not minimize total passenger transfer delay. When SFIFO does not minimize total passenger transfer delay, the sequence that minimizes total passenger transfer delay has higher total costs of aircraft ground time and gate usage because SFIFO minimizes these two costs. Besides, total passenger transfer delay of SFIFO is close to the optimal value. Without $I_m' \approx Q_m'$, for all m, SFIFO may not be the optimal overlapping sequence but is still near-optimal.

When an airport is moderately busy, neither BLIFO nor SFIFO may be the optimal sequence. In addition, the time values of passengers, aircraft, and gates vary in different times and places. As the time value of the gates increases relative to other costs, SFIFO is increasingly preferable to BLIFO. To find the optimal sequence, BLIFO or SFIFO, whichever has the lower total cost, is used to be the initial solution and improved by the sequential pairwise exchange algorithm until no further improvement is possible. However, this improved sequence may not be the exact optimal sequence since the flight sequencing problem is an NP-hard problem (*2*) when an airport is moderately busy.

In this report, the GTW is assumed to be independent of flight sequence, even though the minimum ground times of smaller and larger aircraft are considered. Improved models should explicitly consider how the GTW is affected by a flight sequencing. In addition, the flight sequencing and gate assignment are interdependent. In a previous report Chang (*8*) has analyzed a more realistic flight sequencing problem with a variable ground time window and combined gate assignment, and also has provided extensive numerical results.

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An Optimum Resource Utilization Plan for Airport Passenger Terminal Buildings

MAHMOUD S. PARIZI AND JOHN P. BRAAKSMA

An ideal and practical procedure was developed to optimize resource utilization of airport Passenger Terminal Buildings (PTBs). Each procedure consists of three parts, that is, the PTB operation, an optimization model, and a flow management and control model. In the ideal procedure, it is assumed that a real-time flow management and control technique can be applied on an actual terminal building to dynamically allocate the optimum required resources, obtained from the optimization model, to a highly variable demand. The output of this procedure would be a variable time-resource plan and theoretical optimum operations cost. In the practical procedure, the PTB is simulated using a new object-oriented graphical modelling technique, the SES/workbench. The object and submodel support of this tool allowed rapid development of the simulation model capable of representing a wide variety of PTBs. Statistics from the simulation model are used to develop an optimization model, based on the resource allocation theory, to yield the optimum required resources for each segment of the building at each instant of time. It is also proposed that the results of the optimization model, a variable time-resource plan, can be implemented by application of some site-specific flow management and control strategies. As a result, the procedure will provide a practical variable operational and maintenance cost. How close one can bring the practical cost to the theoretical one depends on the flexibility of the PTB layout and the capability of flow management and control technique.

Capital and operational costs of airport passenger terminal buildings (PTBs) are very extensive. Taking into account the fact that airport PTBs are some of the most expensive public transportation facilities, the goal of public policy should be to ensure that these resources are employed as effectively as possible. A quick review of the existing literature gave the impression that for most of the planning horizon, airport terminals have an oversupply of facilities, for example, space. However, various interest groups are concerned about the negative impacts of insufficient supply during certain time periods, for example, congestion and delays (*1*). Considering that there are undesirable consequences of oversupply as well as undersupply, it is very important to size and operate airport facilities as realistically as possible. Although it may be difficult to design and construct PTBs according to the variable nature of their demand, it is possible to operate them more effectively. This is doubly important with respect to the growth of operating and maintenance costs as the PTB grows in scale and complexity. Factors that contribute to the problem of oversupply and undersupply are summarized.

FACTORS CAUSING THE PROBLEM

The most obvious factor causing the ineffective utilization of airport terminals is traffic peaking. Peaking may be by hour of the day, day of the week, and season of the year. Airport peaking is of course primarily caused by airlines concentrating flights at certain times of the day, days of the week, or seasons of the year. The airline schedule is established based on several criteria, such as the public demand to travel within social hours, the need for arranging connecting services, the utilization pattern of aircraft fleet, and other constraints, for example, night curfews, numerical limitation to night movements, or noise limitations.

The second factor is the current design procedure for PTBs, which determines space requirements according to a broad criterion of average space per person (*2*). For a given traffic level, there is a corresponding space requirement. The traffic level is the forecast demand for a typical hour, that is, typical peak hour passenger (TPHP). Derivation of the TPHP from the existing or forecast data varies among countries, and there is no universally acceptable definition for the TPHP. Even with the standard TPHP, the problem still remains. In theory this is because, assuming the average peak as the 30th busiest hour, the PTB is fully utilized for 1 hour in the year, overutilized for 29 hours in the year, and underutilized for the reminder of the time (8730 hours; there are 8760 hours in a 365-day year) (*3*). In other words, the PTB is overutilized to fully utilized only 0.34 percent of the time each year.

The third factor is that the total system cost is often not visible, particularly those costs associated with operation and support. The visibility problem can be related to the iceberg effect, in which the visible parts are design and construction costs and the remainder (under the water) are operating and maintenance costs. Therefore, the operating cost of PTBs has been almost always ignored in the planning and design process.

The fourth factor is that, in spite of a sensitive relationship between physical planning and operational planning, the analysis of these two is not done early enough. To increase the efficiency of the PTB, two main concepts should be considered in concert: design and operation (*4*). The result of ignoring one of these two concepts would be an inefficient terminal. The combination of a poorly designed PTB with an excellent operational plan may operate well, whereas an excellently designed PTB with a poor operating plan may result in a poorly operating terminal.

The fifth factor associated with the airport PTB design and operation is the month-to-month uncertainty of the airline industry. This creates situations in which terminals designed for one type of operation are forced to operate under a completely different situation because of the bankruptcy of a major airline, and situations in which one carrier is replaced by another carrier with very different scheduling or types of passengers, that is, international versus domestic or hub versus origin and destination operations (*5*). This uncertainty can sometimes render even well-conceived designs inefficient or inappropriate.

However, with the costs and difficulties in modifying the infrastructure to keep pace with the air traffic changes, it would be nec-

Department of Civil & Environmental Engineering, Carleton University, Ottawa, Canada, K1S 5B6.

essary for airport planners to (a) favor a flexible design, (b) prepare an operational plan for different scenarios, and (c) allocate the resources based on the variable nature of demand. One approach to this problem of misallocation of resources is explored in this paper by investigating the application of resource allocation and flow management and control theories to the operation of the PTBs. The hypothesis holds that by applying a flow management and control tool, the resources can be allocated to the variable demand in such a way as to minimize the operational and maintenance cost of the PTB from an airport authority's point of view.

IDEAL OPTIMIZATION PROCEDURE

The PTB is a collection of components to facilitate the transfer of passengers and their baggage from groundside to the airside, or vice versa, and sometimes between airsides. These components are considered as existing resources that are to be utilized based on the traffic demand. Since the demand on the terminal system is stochastic and variable, the utilization of resources should also be variable. Thus, based on the concepts of resource allocation, flow management and control, and the dynamic function of the PTB, an ideal optimization procedure can be developed. The ideal methodology of the proposed optimization procedure is indicated in Figure 1. The process consists of three basic parts, that is, the operation of PTB, an optimization model, and a flow management and control model. Within the operational process, passengers will pass through the PTB according to their prespecified schedules and some operational guidelines. The optimum value of required resources would be found based on the demand placed on the system and performance measures by using an optimization model. These values would be allocated to different segments of the PTB that perform different activities based on some flow management and control techniques. If the resources were allocated as they were found from the optimization model, then the output would be minimum operational and maintenance costs for the PTB at different levels of performance. In the following sections, the theoretical optimization model is formulated, a more practical optimization procedure is developed, and a new object-oriented simulation model is discussed to take the place of a real terminal building.

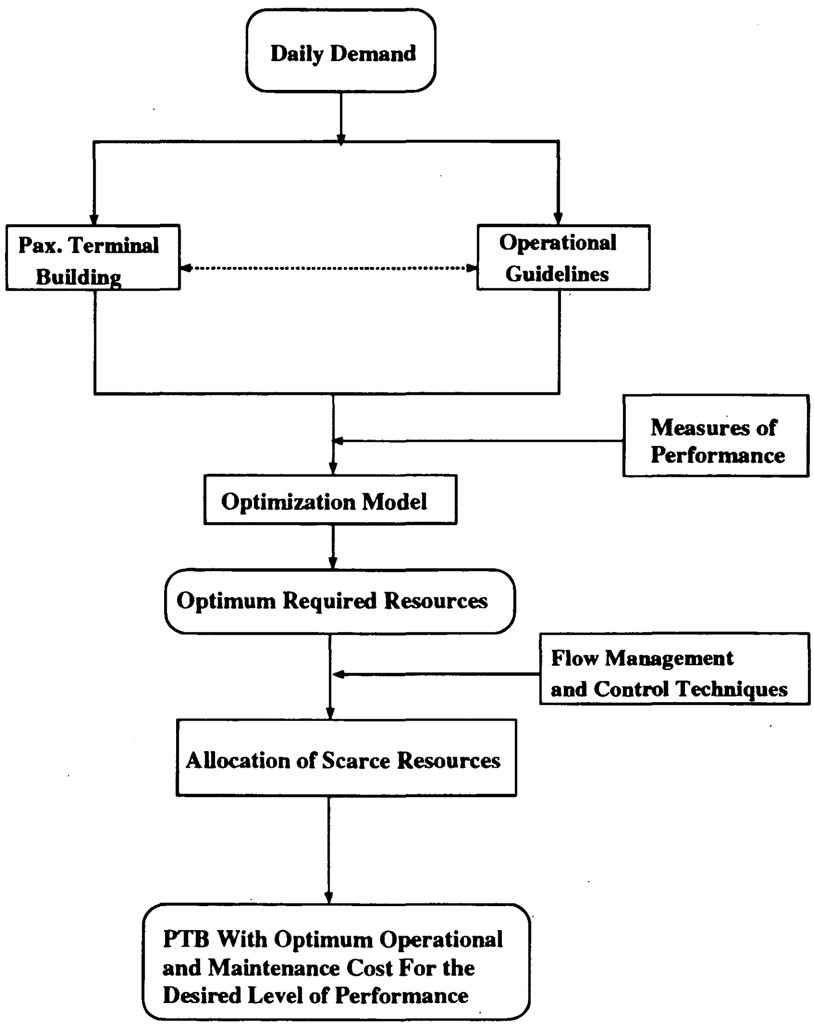

FIGURE 1 Ideal procedure of optimum PTB resource utilization.

Theoretical Analysis

As mentioned earlier, the PTB is a dynamic system mainly consisting of two types of entities, that is, resources and objects (passengers). To optimize the utility of the system, one may deal with either resources or objects or both. In this research, resource allocation theory is used as the basis of the optimization model. In resource allocation theory a fixed amount of resources are allocated to a series of activities with variable demand in such a way that the objective function under consideration is optimized. The resource allocation problem is generally formulated as follows:

$$\text{Minimize } f(x_1, x_2, \ldots x_n)$$
$$\text{Subject to: } \sum_{j=1}^{n} x_j = N,$$
$$x_j > 0, j = 1, 2, 3 \ldots, n \tag{1}$$

That is, given one type of resource, for example, space whose total amount is equal to N, we want to allocate it to n service locations (segments of PTB) which serve an uncertain number of customers so that the objective value becomes as small as possible. The objective function in general form, that is, Equation 1, cannot be used in practical situations. A special objective function for this research problem was developed as follows:

$$\text{Minimize } \sum_{j=1}^{n} c_j(x_j)$$
$$\text{Subject to: } \sum_{j=1}^{n} x_j \le N,$$
$$x_j > 0, j = 1, 2, 3 \ldots, n \tag{2}$$

where

$c_j(x_j)$ = expected cost at segment j when x_j is allocated to j,
x_j = resource for allocation, for example, space,
n = total number of service locations inside the PTB, and
N = total amount of available resource.

The main objective in Equation 2 is to minimize the expected cost function. The difference between Equations 1 and 2 is that in Equation 2 not all of the resources need to be allocated. The expected cost at each location is a function of allocated resources. As mentioned earlier, there are two types of costs associated with the allocation of resources, that is, oversupply and undersupply cost. Moreover, allocation of resources depends on the demand placed on the facility. As a result, the expected cost is also a function of demand. The demand at each location is uncertain and depends mainly on the flight schedule. Taking all the variables into consideration, the total expected oversupply and undersupply cost for the PTB is found as follows:

Assume that y is the demand variable at each service location and $p_j(y)$ is the probability mass function for variable y at segment j. This means that the probability of having y units of demand at segment j is $p_j(y)$. It is also assumed that each unit of demand needs θ_j units of resource at segment j, for example, the amount of space that each passenger occupies. If x_j is the resource allocated to segment j, and α_j is assumed to be the unit cost of oversupply at location j, then the oversupply cost at this location is as follows:

$$\alpha_j \sum_{0}^{\delta_j} (x_j - \theta_j y) p_j(y) \tag{3}$$

where $\delta_j = \text{int}(x_j/\theta_j)$.

If the resources allocated to segment j were less than required, then there would be an undersupply cost. Following the same process and assuming β_j as the unit cost of undersupply, the expected undersupply cost would be:

$$\beta_j \sum_{\delta j}^{y} (\theta_j y - x_j) p_j(y) \tag{4}$$

where Y = maximum expected demand for segment j.

Therefore, the total over and undersupply cost associated with the allocation of x_j resources to segment j is the sum of two preceding cost elements as follows:

$$c_j(x_j) = \alpha_j \sum_{0}^{\delta_j} (x_j - \theta_j y) p_j(y) + \beta_j \sum_{\delta j}^{y} (\theta_j y - x_j) p_j(y) \tag{5}$$

where

$c_j(x_j)$ = expected cost at segment j,
x_j = resource for allocation,
$p_j(y)$ = probability mass function of demand,
θ_j = resource allocated to each demand unit,
α_j = unit cost of oversupply,
β_j = unit cost of undersupply, and
$\delta_j = x_j/\theta_j$.

Since the PTB system consists of several service locations for which resources should be allocated, the total expected oversupply and undersupply cost for the whole system would be as follows:

$$C_T = \sum_{j=1}^{n} c_j(x_j) = \sum_{j=1}^{n} [\alpha_j \sum_{0}^{\delta_j} (x_j - \theta_j y) p_j(y)$$
$$+ \beta_j \sum_{\delta j}^{y} (\theta_j y - x_j) p_j(y)] \tag{6}$$

However, if the resources and demand were assumed to be divisible, then x_j and y are continuous variables that can take any non-negative real values. In this case following the same procedure of indivisibility, the total cost function for segment j would be as follows:

$$c_j(x_j) = \alpha_j \int_{0}^{\delta j} (x_j - \theta_j y) dF_j(y) + \beta_j \int_{\delta j}^{\infty} (\theta_j y - x_j) dF_j(y) \tag{7}$$

where $F_j(y)$ = cumulative distribution of demand at segment j.

If μ_j is defined as the mean of F_j, then by using the principles of probability theory, the preceding equation would finally simplify to:

$$c_j(x_j) = \beta_j \theta_j (\mu_j - \delta_j) + (\alpha_j + \beta_j) \theta_j \int_{0}^{\delta j} F_j(y) dy \tag{8}$$

Considering that $\delta_j = x_j/\theta_j$, then the derivative of the preceding equation with respect to x_j is as follows:

$$c_j(x_j) = -\beta_j + (\alpha_j + \beta_j) \theta_j F_j(x_j) \tag{9}$$

From Equation 8 and its derivative (F_j is increasing) it is clear that the function is convex with respect to variable x_j, which means that there is a minimum point in the function (Figure 2).

According to Figure 2, the operation cost is high before reaching its optimum point. This is referred to as undersupply cost, which is the cost of physical and psychological discomfort perceived by passengers because of the lack of adequate resources. The real value of these costs to the airport operator is difficult to estimate. In some cases they may be roughly approximated by the frequency of com-

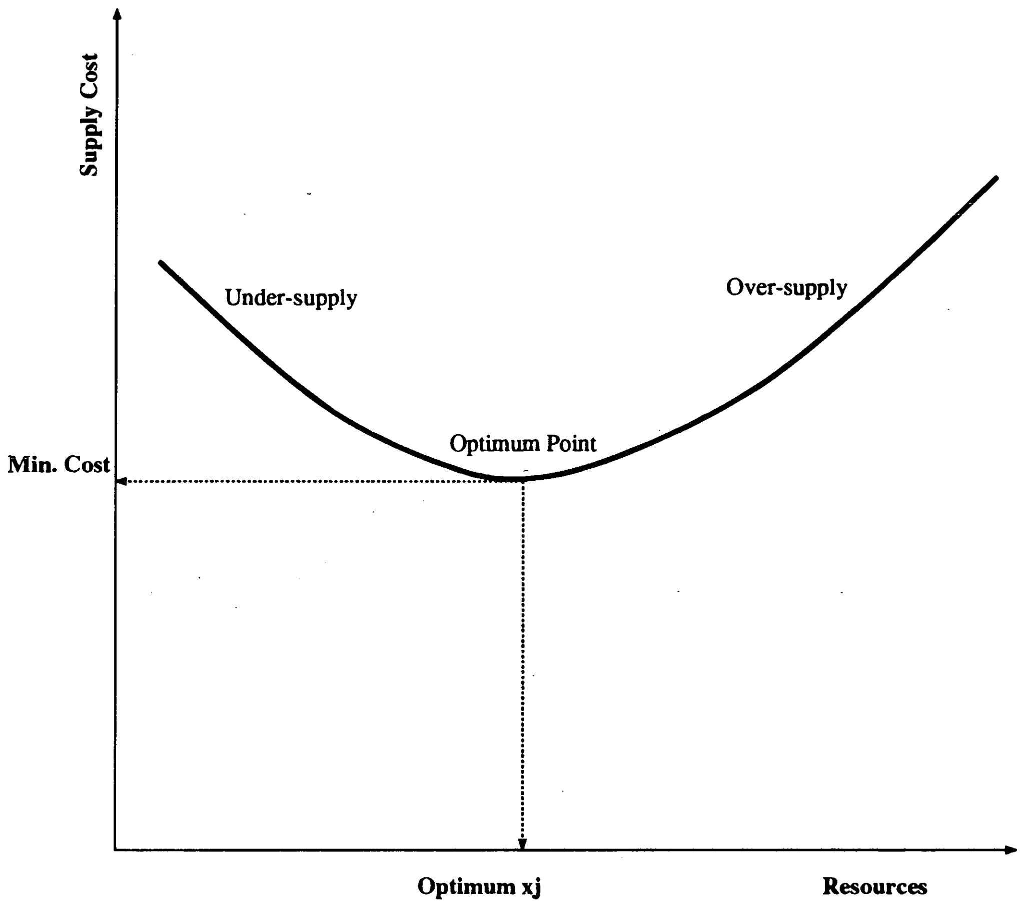

FIGURE 2 Cost function of PTB segments with respect to resource value.

plaints and critical journalism or the loss of potential customers. The operational cost increases right after the optimum point. This is the oversupply cost, which is the cost of providing resources beyond what is required. Having information about operational and maintenance expenses, this unit cost is possible to estimate. However, the objective function would be a series of nonlinear separable convex functions that have to be optimized. If the values of α_j, β_j and the demand function were known, then there would be some analytical approaches to solve such problems as Equation 1, in which the total amount of resources would be allocated (*6*). The objective function of this research problem is more complex than the conventional ones because of the fact that the sum of allocated resources could be less than or equal to the maximum resource available. Moreover, due to the stochastic nature of passenger arrivals and departures at the PTB, no specific mathematical function can represent the actual demand on the system at each instant of time. Therefore, demand function may be found either through an exhaustive data collection exercise for a long period of time, or by using a simulation approach.

PRACTICAL OPTIMIZATION PROCEDURE

The ideal process was believed to be difficult to apply in a real terminal for the time being. Therefore, the three parts of the ideal process were modified to develop a more practical procedure (Figure 3). In the first part of the practical procedure, the PTB is simulated to perform as a real terminal. The simulation model will be discussed in the next section. The simulation is run for a number of days or weeks, and the population statistics are collected for each segment of the PTB during the whole running period. These statistics are analyzed to arrive at the probability mass function (PMF) of demand for each PTB segment. To be as realistic as possible, the operating day is divided into short time periods, for example, 1 hour, and the PMF for each time period is obtained. The PMFs and the values of α and β are used as input to the second part of process, that is, the optimization algorithm. The optimization algorithm determines the optimum value of required resources for each segment at each instant of time. The output of optimization algorithm is a variable time-resource diagram.

The sum of optimum resource values from all segments multiplied by the unit cost of providing resources is the optimum cost of operating the PTB at each instant of time. If all the conditions are met, the operational and maintenance cost will be a function of demand distribution. However, in the third part, it is recommended that the results of the optimization procedure be implemented on the site by some sort of flow management and control technique. The existing resources and the traffic flow should be managed in such a way as to provide a diagram as close to the optimum time-resource plan as possible. The details of the optimization algorithm and the flow management and control model are ongoing research. The results will be the subject of our next paper.

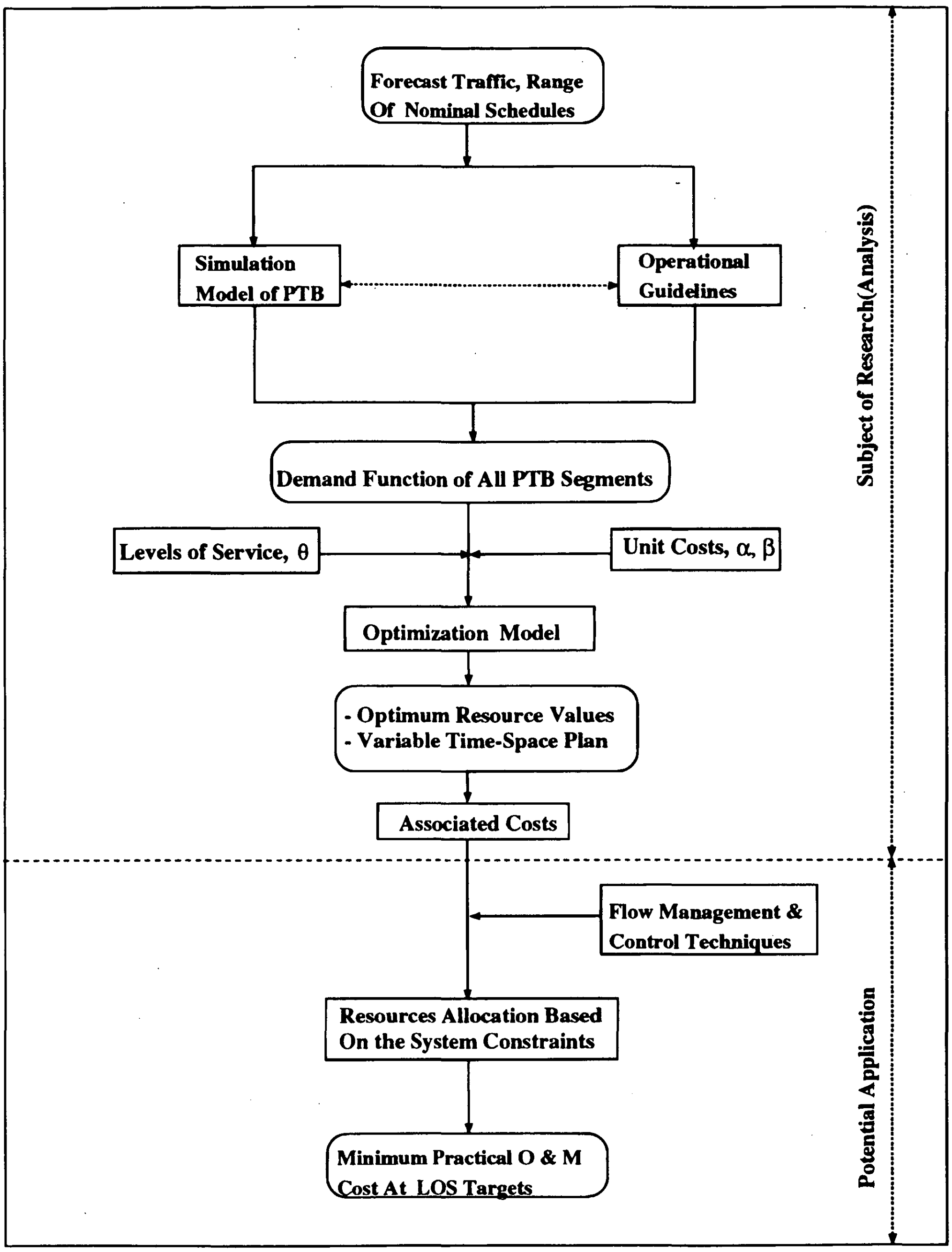

FIGURE 3 Practical procedure of optimum PTB resource utilization.

PTB Simulation Model

Airport terminal simulation models have been developed for more than 30 years (*7*). Through the literature review on existing and currently used simulation models, it was found that models currently available do not respond to the types of issues associated with PTB operation and management. They require extensive programming to fit with any specific configuration of a terminal, take a long time to process any particular run, and require too much detailed information for every run (*8*). An additional problem with currently used simulation models is occasional failures to address important aspects of terminal operations (*9*).

Recently, because of new developments in software technology, there has been a lot of interest to use object-oriented programming (OOP) in PTB simulation. The object-oriented approach has some advantages over conventional languages used in simulation. In summary, the OOP approach is capable of providing immense programming flexibility, greater reduction of input requirements, ease of operation, and user friendliness (*10,11*). OOP also provides fully interactive execution with a high degree of animation and graphics capabilities. The models in the OOP concept are built in terms of real world components of the system, as opposed to reducing components to a series of mathematical relationships and writing computer programs to invoke those relationships. In spite of all of its advantages and interest in the airport industry, a PTB simulation model using OOP is not yet publicly available.

However, for this research, a comprehensive search was undertaken to find the most recent and state-of-the-art simulation tool. A new object-oriented graphical modelling environment, the SES/workbench from Scientific and Engineering Software Incorporated, was found and used to simulate PTB operation (*12*). The SES/workbench is an integrated collection of software tools for simulation and evaluation of complex systems, such as computers, large software systems, data communication networks, and microprocessors. The SES/workbench consists primarily of SES/design, SES/sim, and SES/scope. The graphical representation of the system is built by using the design interface module, SES/design, in which objects are created to represent the various components of the system. The graphical representation is converted to an executable simulation model by SES/sim, a translation and simulation module based on the C and C++ programming languages. Finally SES/scope is an animation module that provides the ability to observe and debug an executing simulation model.

In summary, an SES/workbench model is composed of one or more submodels, each represented by an extended directed graph. The basic components of a graph are nodes, arcs, transactions, and resources. Transactions are entities that flow from node to node along the arcs. Each transaction represents a process to be executed. Each transaction may carry with it an arbitrary user-defined data structure. Each node in a model represents the manipulation, for example, allocation, or release of a physical or logical resource, or some other processing step in a transaction's life. Each arc connects two nodes and is directed from one node to the other. It represents a path along which a transaction may flow from one node to another. Each resource represents some physical or logical component for which transactions compete.

Simulation Model Framework

The PTB simulation model (PTBSIM) is designed to predict the movement of passengers, greeters, and well-wishers for a given terminal design and a candidate commercial aircraft schedule. Throughout the model development every effort was made to keep the model as simple and user friendly as possible. Although the model was developed based on a given terminal design, it is very easy to adjust the model for any type of PTB due to its object-oriented aspect. One can easily change, delete, or copy any node, arc, or submodel to get the desired design. The only required input to the model is an aircraft schedule, which can be entered using any text editor. The aircraft schedule is used to generate passengers and nonpassengers entering the PTB. The operating day is divided into equal time increments, for example, 1 minute long. It should be noted that the size of increments can be any value, for example, from milliseconds to hours.

The PTBSIM was developed as one main module, consisting of six submodels, that is: generate_planes, generate_arrive_pax, generate_depart_pax, process_arrive_pax, process_depart_pax, and concourse. In addition, several functions were developed to define the workload and transaction routing. These functions and some parameters are declared in the three declaration nodes. A brief description of declaration nodes and submodels follows.

In the main_declaration node, two structures are declared as plane and passenger. These two structures consist of a collection of variables (information) which each plane or passenger should carry throughout the model. The structures are declared as "unshared," meaning that each passenger will preserve its own copy of data, including flight number, gate, departure time, and so forth, while passing through different segments of the PTB. Several functions for transaction routing and passenger arrival time sorting are declared in the functions_decs node. In the param_declaration node, several input variables are declared as parameters to include parameters in the model. Parameters can be changed during the runtime, which makes the model user friendly.

The generate_planes submodel is the planeload-generator submodel. A transaction, "seed," is generated, reads each line of the schedule, and generates another transaction called "plane." The plane transaction is routed to either generate_arrive_pax or generate_depart_pax according to its sector, that is, arrival or departure.

The generate_arrive_pax submodel generates arriving passengers. The plane transaction enters the submodel and waits in the delay node for its event time. When the transaction reaches its event time, it generates the number of passengers according to a normal probability distribution, with the mean of average deplaning rate defined by the user. The accumulated number of passengers generated for each increment is compared with the total number of passengers of each aircraft. Once the array of passenger transactions is generated, the plane transaction sends them to the submodel process_arrive_pax.

The submodel generate_depart_pax generates the enplaning passengers and sends them for processing. The plane transaction enters the submodel and after reaching its event time generates the time that each departing passenger arrives at the airport according to a triangular probability distribution. In the triangular distribution, the minimum is defined when the first passenger of the flight arrives at the PTB, the maximum as the time when the last passenger of the flight arrives at the PTB, and mode as the time when the maximum number of passenger arrive at the PTB.

The submodel process_arrive_pax models the activities of deplaning passengers and meeters. Passengers unloaded from the aircraft go to the submodel concourse, to be explained later. Passengers coming out of the submodel concourse will be routed according to their region, that is, domestic, international, and so forth. On arrival of domestic passengers to the baggage claim area, meeters will be generated according to a uniform probability distribution ranging from 0 to 2. The international passengers will go through the preliminary inspection lines (PIL) (Canada Customs and Immigrations), secondary customs, immigration, the baggage claim area, and the arrival lobby. The service times for all these activities are drawn from some probability distributions in which mean and standard deviation are based on historical data (*1,13,14*).

The process_depart_pax submodel models the behavior of enplaning passengers and well-wishers. Departure passenger transactions are accompanied with the well-wishers. Well-wishers are generated from an integer uniform probability function. Almost all the passengers and well-wishers go through the ticket lobby. A percentage of passengers either are preticketed or go to the express check. Each major airline and its allied carriers is represented by a service node with some number of servers. Passengers are directed to the service nodes according to their flight numbers. Depending on how much time is left for each passenger before departure, the passengers may stay in the waiting and concession area. If the time left for the passengers is too short, then the passengers will experience only the walking-time delay. Passengers and their companions proceed to the security booths and gates through corridors or some vertical transportation facilities, such as escalators, elevators, or

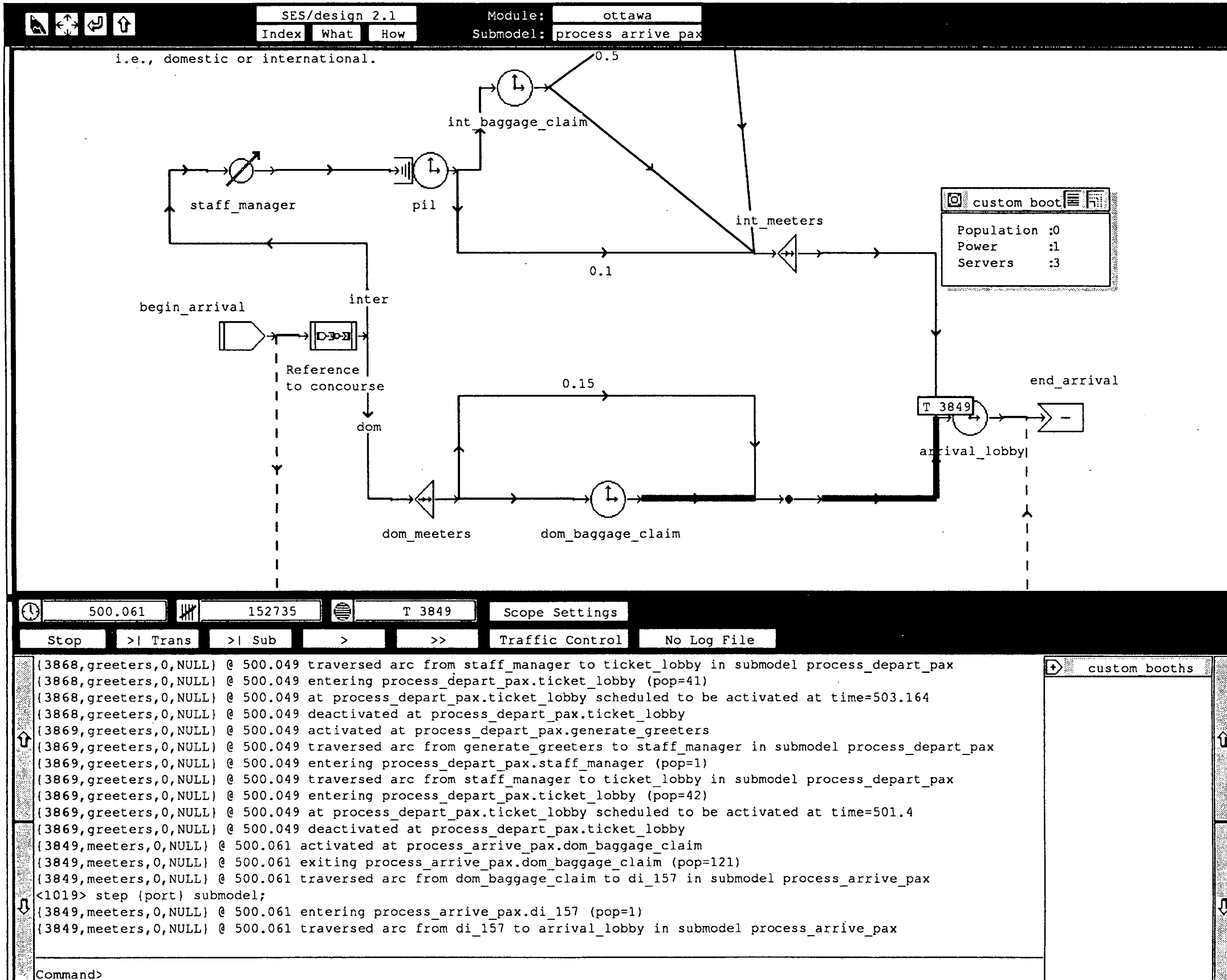

FIGURE 4 Illustration of SES/design and SES/scope window.

moving belts. Only passengers are allowed to pass the security and to go to the concourse. It should be noted that the number of servers in each service node, that is, PTB personnel, is dynamically managed over time by a set node called staff_manager.

The concourse submodel is a waiting area with several gates. Both arrival and departure passengers will go through the concourse area. The arrival passengers experience a delay time equal to their walking distance divided by their walking speed, and the departure passenger enters the concourse and waits until the final boarding call. Therefore, each passenger will experience a different amount of delay time. The reason for making the model into six submodels is to make the model flexible enough for possible adjustments of specific PTBs.

PTBSIM Evaluation

When the basic layout of the model was constructed, the SES/scope was used to calibrate the model. SES/scope allows the modeller to interact with, control, and debug the model while it is running. It also allows one to watch an animated display of the model's execution and to debug the model should it behave in unexpected ways. One can interact with the animation of a running model through the SES/scope window below the SES/design window. An example of the window is indicated in Figure 4. All the trace messages and other information about the model's state are displayed in the SES/scope window. One can enter control commands at the command line prompt below the SES/scope window. At the top of SES/scope window is a banner containing several buttons that are used to control various animation parameters, and fields that display information about the current state of the model.

While SES/scope is active, one may examine specification forms, defined for the nodes in the graph, displayed in the SES/design window. In the case of any unexpected behavior of the model, the specification form may be checked for tracing the problem. After the debugging process, one may calibrate the model using the animation capability. SES/scope provides a detailed animation of the model events as the model runs. Modellers also have control over the events that they choose to see animated. Some of the events that can be animated are transaction movement, transaction tracking, transaction creation and destruction, service and delay nodes, and queue entry and exit.

For example, as a passenger (transaction) flows through the PTB, for example, traverses arcs and enters nodes, it is represented by a rectangle containing a "T" (for transaction) followed by the transaction identification number (Figure 4). The most recently traversed arc is thickened considerably. This permits one to observe visually the paths that specific transactions follow as they flow through the model. Modellers control the scope of animation by using the buttons and defining them according to their own needs. For example, one may choose to animate a specific category of passengers, a specific service node, or a submodel. Using the SES/scope, the debugging process was done and the PTBSIM was finetuned based on data obtained from the Macdonald-Cartier International Airport in Ottawa, Canada.

The general objective of the validation procedure for PTBSIM was to demonstrate the extent of agreement between model outputs and corresponding data obtained at the airport. Data observed for this purpose are time series of flow and queue length at passenger processing facilities. Data were collected by stationing observers at several locations throughout the PTB for simultaneous observation of the population at each processing unit. The model is also capable of producing time series data for direct comparison with field observation. The outputs from the PTBSIM and observed data versus time were plotted on the same pair of axes for visual comparison.

The model provided generally good representation of those facilities surveyed, as illustrated in Figure 5. More complete discussion

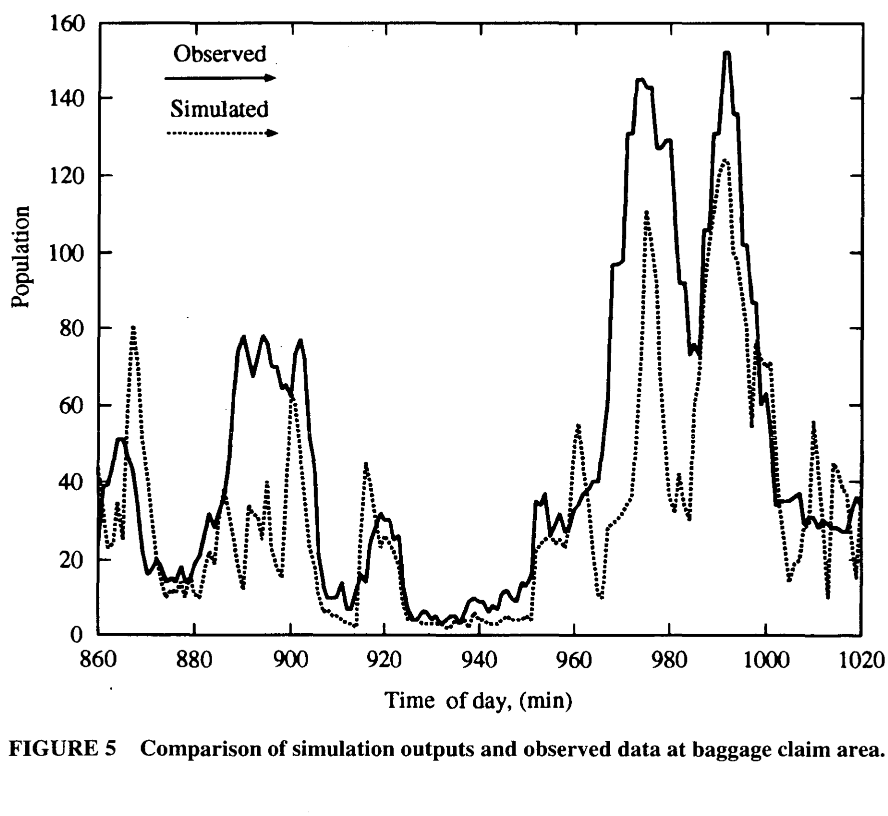

FIGURE 5 Comparison of simulation outputs and observed data at baggage claim area.

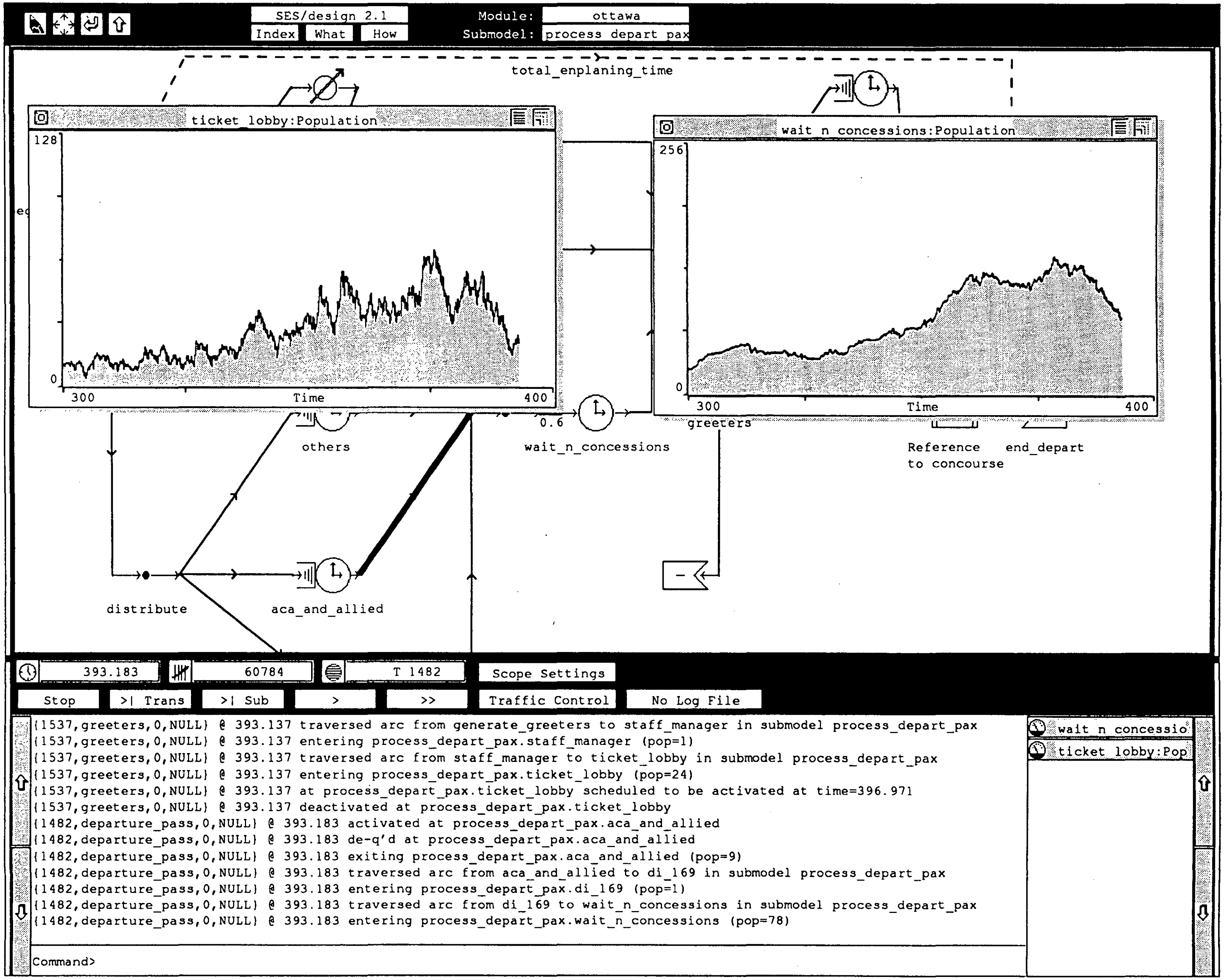

FIGURE 6 Real-time graphic illustration of statistical results.MDNM/.

on the results of simulation can be found elsewhere (*15*). The model can also be validated in some degree through SES/scope. Running in SES/scope, one can see the graphic illustration of some statistics, such as population, queue length, and so forth. Figure 6 indicates the population statistics against time for several segments of the PTB. The modeller would be able to change the parameters and observe the consequences graphically. The graphs can be zoomed for more detail illustration.

Although the visual approach indicates an agreement, the extent to which the model can replicate the existing situations is another important aspect to statisticians. PTBSIM also outputs a list of statistics, for example, mean, standard deviation, maximum, and minimum for some parameters defined throughout the model, such as population, queue length, waiting time, and utilization. These statistics are very useful for overall performance evaluations of the model. In addition, the Statistical Package for Social Science (SPSS), a program utilizing the least square method, was used to find the degree of correlations between the observed and simulated values (*16*). By looking at the results and taking into account the stochastic nature of passenger activities, it appears that the model can reasonably predict the behavior of passengers in the PTB. As already mentioned, by changing some input variables, any terminal building can be modeled. Moreover, in a specific PTB, any operational plan can be generated and tested very easily. Therefore, the PTBSIM is not only a simulation tool but an evaluation tool as well.

Conclusions and Future Research

The optimization procedure described in this paper can be used as a utilization plan to operate the PTB at its minimum total oversupply and undersupply cost. The procedure can also be used as a short- or long-term planning tool. Given a nominal aircraft schedule, the planner would be able to simulate the basic activities and services required for a passenger terminal. Using the statistics obtained from the simulation as input to the optimization model, a modeller will get a variable time-resource diagram. The diagram could be daily, weekly, monthly, or yearly depending on the accuracy of the analysis. The designer can use these diagrams to prepare a more flexible and efficient physical layout. Therefore, there would be a better association between the physical and operational plans at the early stages of planning.

The idea of flow management and control can respond to some real-time events which may happen due to an uncertain economy, bankruptcy or replacement of a carrier, traffic demand changes, or even natural factors such as inclement weather.

Using the PTBSIM, the airport operator would be able to place the demand on the PTB system and observe its operation. The operator can also interactively test the PTB operation under different load conditions or operational plans. PTBSIM can also be used as an operations tool for the operating staff to help them to maintain a reasonable level of service through the PTB.

The use of SES/workbench to simulate the PTB instead of using more conventional simulation languages reduced the simulation time substantially without reducing the overall accuracy of results.

However, to implement the practical optimization procedure, more research is needed. At present, research is proceeding to develop a heuristic optimization algorithm that can be combined with the simulation model. The procedure will be tested on different passenger terminals and the results will be compared.

ACKNOWLEDGMENT

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Analysis of Moving Walkway Use in Airport Terminal Corridors

SETH YOUNG

This paper explores the use of pedestrian conveyor systems, otherwise known as moving walkways, in long public corridors such as those found in major commercial airports. The investigation includes a brief comparison of moving walkways with other primary modes of airport terminal passenger transportation and an empirical study of the use of moving walkways through analysis of passenger conveyors at the United Airlines Terminal at San Francisco International Airport. The empirical study investigates the physical characteristics of several conveyors and their locations within the airport terminal. The study also examines the passengers that traverse the corridors where the moving walkways are located. Characteristics of the passengers, along with their "mode choice" of transport along the corridor were recorded. With these data, a brief examination of current passenger use is made, with an emphasis on how travel speeds vary with each mode. In addition, implications are drawn concerning a passenger's mode choice, by means of two discrete choice Logit models. The paper briefly compares the findings from the empirical analysis with similar studies performed in Europe in the 1970s. The comparison determines improvements that have been made since the European studies. Finally, the paper draws some speculations as to how characteristics of passenger conveyors may be altered, in hopes of improving their services and ultimately increasing their niche in the pedestrian transport market.

First proposed over 100 years ago, the moving walkway, or motorized passenger conveyor, has been considered an innovative mode of pedestrian transportation. The first public operational moving platforms carrying pedestrians were found at entertainment complexes (such as the 1893 World's Colombian fair in Chicago) and were considered as novelty items. The first effort to implement a conveyor system solely for the purpose of serious passenger transport occurred in 1904, with a proposal to build a continuous moving walkway subway under 34th street in Manhattan, New York, but was never implemented successfully. Few such systems were actually operational in the United States before 1950, the most successful of them being Cleveland, Ohio's "Rolling Road," which transported pedestrians as well as horse and carriages from the low-lying warehouse district to the downtown, some 20 meters higher in elevation. Virtually all operational moving walkway systems were defunct by the early 1950s.

Modern times have shown a rebirth in the passenger conveyor. The moving walkways, however, have been relegated to particular market niches. Conveyors are now primarily found at indoor facilities such as sporting arenas and auditoriums. Most significantly, they are found in major transportation-oriented facilities, such as rail stations, parking garages, and airports. Airports, in fact, are the most predominant users of moving walkways. Because of the large areas required by aircraft for maneuvering, the large number of pedestrians passing through airports, and the large percentage of those passengers carrying baggage, airports, in theory, are ideal locations for moving walkways.

Airport terminals have had a unique experience with passenger conveyor systems. Over the years, airports have acted as testing grounds for technological modifications to passenger conveyors. In addition, airports have provided unique arenas for competition between passenger conveyors and other passenger-mobility systems, such as electric courtesy carts, people movers, and buses. With each mode's inherent advantages and disadvantages, present conveyor technology has found its niche within the airport terminal environment. This paper will discuss briefly the characteristics that have determined its current limited success and provide insight into how modifications to the passenger conveyor may result in success in more areas of society.

Institute of Transportation Studies, University of California, Berkeley, Berkeley, Calif. 94720

PRESENT DAY PASSENGER MOBILITY SYSTEMS

Airports are ideal locations for pedestrian mobility systems for a variety of reasons. The grand scale of most airport terminals and the need for baggage-encumbered passengers to move long distances quickly creates a demand for enhanced mobility.

Airline hub-and-spoke route configurations have increased terminal sprawl while reducing a passenger's time frame for making connecting flights. Therefore, interchanging passengers must be able to move through the terminal quickly to switch flights. Furthermore, passengers must deal with the long distances associated with large-scale terminal buildings that are continually growing as air traffic grows.

There are a number of pedestrian movement technologies available to airports. Presumably, the primary reason for such technologies is to reduce the passengers' travel times throughout the terminal environment. The four primary technologies in use today are as follows:

- Courtesy carts,
- Buses,
- Automated people movers (APMs), and
- Moving walkways.

Articles by Leder (*1*), Smith (*2*), and Sproule (*3*) present comprehensive reviews of each of the above modes, describing the technology of each mode, performance measures, and inherent advantages and disadvantages. Table 1 compares the four primary transport modes. The advantages, disadvantages, and primary market niches for each mode are described.

Courtesy Carts

Courtesy carts are highly maneuverable, electric powered, rubber tired vehicles that can navigate though a terminal concourse shared

TABLE 1 Performance Characteristics of Passenger Mobility Systems

Mode	Typical Operating Speed	Headway	Capacity
Courtesy Cart	4 - 8 km/hr.	variable	5 pax/cart 150-200 pax/hr
Bus	16 - 55 km/hr.	5 - 15 min.	15 - 60 pax/bus 500 - 1500 pax/hr
APM	13 - 80 km/hr.	1 - 5 min.	1,000 - 14,000 pax/hr.
Moving Walkway	30 m/min.	none	typical: 5,000 pax/hr.

with pedestrians, furniture, fixtures, and building components with ease. Carts are typically used in three cases.

- To transport mobility-impaired passengers who cannot walk long distances or whose walking speeds are well below normal;
- To transport passengers making close connections when above normal walking performance would be insufficient; and
- To provide organized service over a fixed route.

The flexibility of deployment and scheduling, along with the potential for operation without dedicated building infrastructure are two primary advantages of the carts. The largest disadvantages include unscheduled, hence unreliable, service, the low capacity of the mode, and the potential of corridor gridlock in congested areas. Furthermore, courtesy carts are generally disliked by those pedestrians who do not use the mode, due to their apparent intrusion into the pedestrian corridor, and the potential for pedestrian safety compromises. Courtesy carts can serve an important role in assisting the mobility-impaired and connecting passengers with a time shortage, but they are not viable for significant ridership levels because of their physical design and operating environment.

Buses

Buses are rubber-tired, driver-steered vehicles operating mostly on streets and roads in mixed traffic. At airports they typically operate on terminal frontage and circulation roadways on a nonexclusive basis, providing both scheduled and on-demand service to defined curbside stops that are easily relocated. They are used typically for transporting passengers between major airport facilities, such as between terminal buildings, parking areas, and regional public transit systems.

Some advantages of this mode are its flexibility, relatively low cost, and high capacity. The biggest disadvantage is its observed quality of service. Buses are often considered "uncomfortable," and air passengers with baggage often are unwilling to tolerate either crowds or long wait times. Because of their curbside stops, buses are inconvenient for connecting passenger transportation, and airport congestion keeps service speeds low.

Automated People Movers

An APM is a class of public transit characterized by its automatic driverless control of discrete vehicles operating on exclusive rights-of-way, using a specialized guideway to control the vehicles' path. Because APMs are proprietary systems, many technological features vary between suppliers.

APMs typically have high passenger acceptance because of their outstanding safety and service record. However, these systems have high facility and maintenance requirements. As a result, APMs are best suited to relatively high rider levels over routes longer than 300 meters, although shorter alignments in specialized situations do exist.

Moving Walkways/Passenger Conveyors

The conventional moving walkway is a pedestrian-carrying device on which passengers may stand or walk. Propulsion is provided by a treadway that moves at a constant, uninterrupted speed and offers point-to-point service. Nominal lengths vary from 30 to 120 m. Local building codes often govern maximum lengths on the basis of emergency exit requirements. Treadway widths typically range from 100 cm (most prevalent) to 140 cm. Inclines of up to 15 degrees are possible. Treadway speeds are typically between 25 and 35 m/min. 30 m/min is the typical operating speed. Regard for passenger safety prevents higher operating speeds. The capacity of a moving walkway varies with its environment, depending on the speed of the treadway and the foot speed of passengers, among other variables. Practically, moving walkway systems have been found to have capacities of about 5,000 passengers per hour per direction.

Walkway facilities have their inherent advantages and disadvantages. A moving walkway speed of 30 m/min is considerably lower than the average pedestrian walking speed of 70 m/min. Another disadvantage is the small width of the typical walkway. This is a particular problem in airports where luggage-laden passengers walking on the conveyor wish to pass other luggage-laden passengers standing still on the conveyor. Further disadvantages of the system are the barriers to cross-concourse traffic, the inaccessibility to wheelchair or otherwise mobility-impaired passengers, and the inflexibility of the system. Some advantages of the system include the fact that there are no headway and, hence, no waiting time for service, unless the arrival of passengers exceeds system capacity. The system is perceived to be safe and simple and may be integrated easily into any airport terminal environment. Maintenance of the system is also relatively simple. Careful maintenance planning is required, though, because any system stoppage during periods of terminal activity could cause severe inconvenience and because there is no quick-fix or backup system typically available.

An excellent review of the historical evolution of moving walkway technology, including a description of the three main types of moving walkways in use today (rubber belt systems, cleated pallet systems, and rubber covered pallet systems), may be found in John Tough and Coleman O'Flaherty's book entitled *Passenger Conveyor: An Innovatory Form of Communal Transport* (*4*).

Knowing the inherent characteristics of moving walkways, such pedestrian transport systems appear in theory to fit quite well in the airport environment. Despite this theory, however, little has been studied concerning the use of the conveyors empirically. What follows is one such study. Specifically, a case study of the moving walkways at the United Airlines Terminal at San Francisco International Airport is made, with the goal of determining who uses the moving walkways, how, and when, depending on the characteristics of the moving walkways, the corridors in which they are located, and the passengers that travel the terminal corridors.

ANALYSIS OF MOVING WALKWAYS: UNITED AIRLINES TERMINAL, SFO

Methodology

The United Airlines terminal at the San Francisco International Airport has four sets of passenger conveyors for public use. They are located as follows:

- Between gates 80 and 84, after security check;
- Immediately after security check, before gates;
- Corridor between parking garage and check-in counters; and
- Between gates 84 and 87, after security check.

Conveyor banks 1 through 3 were visited on Sunday, April 24, 1994, between 3:00 p.m. and 6:00 p.m. The following physical characteristics of each conveyor system were surveyed:

- Treadway belt speed;
- The number of belts in each direction;
- "Departure" direction = heading toward the farthest gates;
- "Arrival direction" = heading toward the parking garage;
- The incline of the corridor (in degrees);
- The length of the conveyor; and
- The width of the conveyor belt.

Table 2 describes the observed characteristics of the conveyors.

At the time of the study, the arrival direction conveyors in conveyor bank 2 were closed for maintenance. After recording the above data, observations regarding how each conveyor was utilized were made. At each site, pedestrians were selected randomly for observation on passing a predetermined entrance threshold in the corridor. This threshold was determined to be an imaginary line along the corridor floor perpendicular to the entrance to the conveyor and approximately 5 m before the entrance to the conveyor. This location made it possible to observe passengers who were dedicated to traversing the corridor but had not yet committed to his/her mode of transport. During this time, the following passenger data were collected:

- The passenger's approximate *age*, to the nearest decade;
- The passenger's *sex*;
- Whether the passenger was a *business*- or *leisure*-type traveler; and
- The *number of bags carried* by the passenger.

The above characteristics were made using the best judgment of the observers. Although age and sex characteristics appear clear to assess, passenger *type* may be unclear. Characteristics of the person's attire and type of baggage were the two factors most keenly observed to determine the purpose of the passenger's trip. For instance, an adult in a business suit carrying a briefcase was noted to be a business traveler, whereas a child in casual clothes carrying a teddy bear was noted as a leisure traveler.

The amount of baggage was recorded in the following manner. For the purposes of this study, any item larger than a purse was considered to be a baggage item. No discrimination as to the weight of an item was made. Although the method an item was carried (e.g., over the shoulder, toted along wheels, or lifted) was recorded, analysis later revealed that this characteristic had little effect on conveyor use and was dropped from the study.

As the traveler crossed the conveyor threshold, it was recorded whether (s)he entered onto the conveyor or bypassed it. If the person chose to use the conveyor, it was recorded whether the person stood still and traveled at the speed of the conveyor, or walked along the belt. Finally, the duration of travel from the entrance threshold to the exit threshold was recorded. The exit threshold was defined as an imaginary line where the conveyor belt ends, marking the point where the presence of the conveyor has no bearing on the passenger's travel. This observation defined the three modes of transport along the corridor, STAND, WALK, or BYPASS, and provided complete measurements on the time each passenger needed to traverse the corridor, given his/her mode choice. A total of 269 observations were made during the observation period.

Analysis of Observed Data

Initial analysis of the sample revealed that a vast majority of the sample did use the conveyors in some fashion (i.e., either chose mode STAND or WALK). Of these, approximately one-third of the conveyor users stood still on the conveyor belt. The distribution of mode choice, as well as the average travel speed and travel time of each group of passengers, is illustrated in Table 3.

The most striking results to come out of this initial analysis was that the average travel speed for passengers using the conveyor (STAND/WALK combined) was only marginally higher than for those who chose BYPASS the conveyors. Moreover, the average travel time to traverse the corridors was almost 7 sec higher for those using the conveyors than for those bypassing. These initial results prompted two further forms of analysis, one to further explore changes in passenger foot speed and one to evaluate the mode choice made by passengers.

TABLE 2 Conveyor Characteristics

Conveyor	Speed (m/sec)	# belts (dep.)	# belts (arr).	Slope(°)	Length (m)	Width (cm)
1	0.64	1	1	0	85	100
2	0.64	1	2	0	120	100
3	0.64	1	1	+2° arr.	80	100

TABLE 3 Mode Choice Distribution

Mode	# Sampled	% Total	Avg. Speed (m/sec)	Avg. Time (sec)
STAND	57	21 %	0.67	135
WALK	146	54 %	1.70	59.18
USE	**203**	**75 %**	**1.41**	**80.47**
BYPASS	66	25 %	1.36	73.20

Analysis of Changing Foot Speeds

The above initial observation prompted a deeper analysis of changing walking pace for those using moving walkways. This analysis studies the changing foot speeds of passengers choosing to WALK. The analysis was performed for each conveyor in each operable direction.

For each conveyor in the study, the noted conveyor belt speed and average walking pace for a bypassing passenger were summed together to determine a theoretical travel speed for a passenger who chooses to WALK on the conveyor without changing natural foot speed. This theoretical speed was then compared with the average walking speeds for each location. The results of these calculations are found in Table 4. The results show a decrease in walking speeds ranging from 0.15 to 0.45 m/sec for passengers walking on conveyors. Further analysis, breaking down the sample of passengers into groups according to similar characteristics, revealed no significant departure from the overall decrease in walking speed.

This consistent decrease in walking speeds may be primarily due to the physical characteristics of the conveyor. The narrow width, rubber-belt footing, and belt speed of the conveyor all contribute to passengers slowing their step when walking. Furthermore, the walking speeds tended to be slow for conveyors having a higher passenger flow, and hence higher degrees of congestion.

Mode Choice Analysis

To explore the mode choice made by passengers, analysis was performed by the evaluation of two discrete choice Logit models, each with one independent variable. The first model evaluated the three mode choices (STAND vs. WALK vs. BYPASS) using the independent variable travel speed. The second model evaluated the same choices using the independent variable, travel time, which takes into consideration the length of the corridor traversed.

The Logit analysis was performed using the *ALOGIT* computer software package. To successfully run *ALOGIT*, a proper data set must be used. Such a data file required data that could not be observed directly in the field. Specifically, the travel times and travel speeds for the two modes that a passenger did *not* choose when traversing the corridor could not be observed and recorded. An estimation of these alternative choice attributes was made by the following methodology.

Estimation of Alternative Choice Attributes

STAND

For those passengers who did not choose STAND, the travel speed and travel time values for the alternative STAND were merely calculated as follows:

Travel Speed = Belt Speed
Travel Time = Belt Speed * Length of Conveyor

WALK

For those passengers who did not choose WALK, a linear regression model was applied. The regression was based on those passengers who did choose WALK, and the characteristics of their environment when the choice was made. The specific characteristics included in the regression were as follows:

X_1 = Corridor/Conveyor Length (m). (1a)
X_2 = Belt Speed (m/sec.). (1b)
X_3 = Congestion level of the conveyor (1 = congested, 0 = uncongested). (1c)
X_4 = The incline (slope) of the corridor (degrees). (1d)
X_5 = The age of the passenger (to the nearest decade). (1e)
X_6 = The sex of the passenger (1 = male, 0 = female). (1f)
X_7 = The "type" of passenger (1 = business, 0 = leisure). (1g)
X_8 = The number of bags carried by the passenger. (1h)

(Note: The following analysis was performed using data measured in U.S. units. Resulting formulations were adjusted to metric units after analysis was performed.)

TABLE 4 Changing Foot Speeds, by Conveyor

Conveyor	1 Dep.	1 Arr.	2 Dep.	3 Dep.	3 Arr.
Bypass Speed (m./sec.)	1.34	1.36	1.18	1.60	1.40
Belt Speed (m./sec.)	0.64	0.64	0.64	0.73	0.73
Bypass + Belt Speed (m/sec)	1.98	2.0	1.82	2.33	2.14
Conveyor Length (m.)	85.4	85.4	119.3	79.3	79.3
Est. Travel Time (sec.)	43.08	42.75	65.48	33.97	37.13
Obs. WALK travel time (sec.)	46.97	51.84	88.44	55.00	49.00
WALK + Belt Speed (m./sec)	1.82	1.65	1.35	1.44	1.62
Obs. WALK foot speed (m/sec)	1.18	1.01	0.71	0.70	0.89
Change in foot speed (ft./sec)	**-0.16**	**-0.35**	**-0.47**	**-0.89**	**-0.52**

Table 5 displays the resulting linear regression coefficients that were used to estimate the total travel speed and travel time of the passengers should they have chosen to WALK:

(Note: All regression equations are of form:
$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n$) (2)

Initially, only the travel speed independent variable was considered for regression analysis. Travel time was to be estimated by merely multiplying the estimated speed by the corridor length. Further consideration, however, brought on the hypothesis that the length of the corridor itself may have a significant effect on the travel speed of a pedestrian. This may be most prevalent in those who chose to WALK along the conveyors. Along longer corridors, for example, several passengers were observed to STAND on the conveyor for a portion of the trip, and then begin walking for the duration. To test this hypothesis, estimated travel time data from the above regression equation was compared with simple *time = length * speed* results against true data for those who did indeed WALK. The regression equation did produce a better match to the true data. The results of the simple formula tended to underestimate those whose true travel time was on the high end of the spectrum.

It is interesting to note that belt speed has a negative effect on total travel speed across the corridor. This enriches the above analysis of changing foot speeds when walking on conveyors. Another interesting result of this regression was that the speed increases with increasing numbers of bags carried. One explanation for this may be that those passengers with more baggage tended to be in more of a rush to catch their flights than were those with fewer bags. Other independent variables appear to have intuitive effects on travel speed and time, which further justifies the use of the equations in the estimation process.

BYPASS

For those passengers who did not choose to BYPASS the conveyor, a similar regression analysis was performed to estimate their BYPASS speeds and travel times. The variables used in the regression were those that would have had an effect on their bypass speed or travel time, respectively. Table 6 lists the values that represent coefficients in the travel speed and travel time equations.

Again, it is interesting to note the increase in travel speed and similar reduction in travel time with increasing numbers of bags carried. Other variable coefficients appear more intuitive.

A successful run of *ALOGIT* using the Travel Speed data produced the following utility functions for each mode choice:

WALK: $U_W = 0.7241 + 0.076 TS_W$ (3a)
STAND: $U_S = 0.0326 + 0.076 TS_S$ (3b)
BYPASS: $U_B = 0 + 0.076 TS_B$ (3c)

A few interesting observations may be made from these functions. The most distinguishing characteristic is the positive alternative specific constant in the STAND mode utility function. More importantly, the constant is higher than that of the base mode, BYPASS. This implies that standing indeed may carry a higher utility for those whose normal foot speeds are very close to the speed of the belt. Pedestrians of older ages, as well as those with physical impairments may easily fit this category (it is interesting to note that age was indeed one of the more significant variables in the travel speed regression analysis).

Applying the above utility functions into the Logit model reveals some interesting issues. In comparing two hypothetical passengers with the following travel speed characteristics:

"Healthy"	"Impaired"	
$TS_W = 6.0$ ft/sec	$TS_W = 4.5$ ft/sec	(4a, 4b)
$TS_S = 2.1$ ft/sec	$TS_S = 2.1$ ft/sec	(4c, 4d)
$TS_B = 4.6$ ft/sec	$TS_B = 3.0$ ft/sec	(4e, 4f)

the following utility values are derived:

$U_W = 1.18$	$U_W = 1.07$	(5a, 5b)
$U_S = 0.192$	$U_S = 0.19$	(5c, 5d)
$U_B = 0.349$	$U_B = 0.023.$	(5e, 5f)

Applying these utility values to a Logit function of the form:

$$P(\text{mode x}) = \frac{e^{Ux}}{e^{Ux} + e^{Uy} + e^{Uz}} \quad (6)$$

The following mode choice probabilities are found:

	"Healthy"	"Impaired"	
P(WALK)	0.55	0.57	(6a, 6b)
P(STAND)	0.21	0.23	(6c, 6d)
P(BYPASS)	0.24	0.20	(6e, 6f)

TABLE 5 Regression Coefficients, WALK Alternative

Coefficient	Travel Speed (TS_W)		Travel Time (TT_W)	
α	+ 2.485	(t = 1.22)	+ 54.46	(t = 0.56)
β_1	- 0.003	(t = -0.20)	+ 0.01	(t = 0.05)
β_2	- 1.086	(t = -0.70)	+ 4.79	(t = 0.22)
β_3	- 0.363	(t = -0.22)	+ 35.19	(t = 1.48)
β_4	- 0.17	(t = -1.40)	+ 1.05	(t = 0.60)
β_5	+ 0.005	(t = 0.45)	- 0.28	(t = -1.77)
β_6	+ 0.217	(t = 0.79)	- 4.25	(t = -1.10)
β_7	+ 0.34	(t = 0.90)	- 6.10	(t = -1.13)
β_8	+ 0.178	(t = 0.98)	- 3.44	(t = -1.34)
ρ^2	0.07		0.30	

TABLE 6 Regression Coefficients, BYPASS Alternative

Coefficient	Travel Speed (TS_B)		Travel Time (TT_B)	
α	+1.380	(t = 11.01)	-34.00	(t = -3.75)
β_1	0		+ 0.35	(t = 13.92)
β_2	0		0	
β_3	0		0	
β_4	-0.11	(t = -0.92)	+ 1.64	(t = 1.10)
β_5	+ 0.01	(t = -0.83)	+ 0.04	(t = 0.30)
β_6	+ 0.33	(t = 1.37)	- 1.74	(t = -0.57)
β_7	+ 0.073	(t = -0.23)	- 1.68	(t = -0.42)
β_8	+ 0.212	(t = 1.41)	- 3.69	(t = -1.96)
ρ^2	0.12		0.79	

These probabilities are highly consistent with the proportion of passengers' mode choices in the sample data.

From the similarities in mode choice probabilities, as well as from direct inspection of the travel speed coefficient of 0.076 in the utility functions, it can be inferred that the sensitivity of travel speed to mode choice is quite low. Although in the above comparison the probability of choosing STAND does make the shift to exceeding the probability of BYPASSing, the overall difference in probability values between the "healthy" person and the "impaired" passenger are marginal.

An interesting issue arises when comparing the results of the travel speed model with the travel time model. An *ALOGIT* run successfully made using the above collected data and regression derived travel time values resulted in the following utility function for the three mode choices:

$$\text{WALK: } U_W = 0.932 + 0.01584TT_W \quad (7a)$$
$$\text{STAND: } U_S = -1.287 + 0.01584TT_S \quad (7b)$$
$$\text{BYPASS: } U_B = 0 + 0.01584TS_B \quad (7c)$$

The primary issue to strike the observer when comparing travel time utility functions with the travel speed functions is the magnitude of the difference between the variable coefficients and the alternative specific constants. The travel time model has much higher alternative specific constants relative to the independent variable coefficient, marking a significantly less sensitive variable in travel time. What tends to drive the travel time utility functions are the alternative specific constants, which set an immediate significant utility ranking. WALK is clearly the most preferable mode, followed by BYPASS, and STAND is a distant third choice. Only as travel times for STAND increase with rates significantly higher than for BYPASS and WALK will STAND ever become a preferable choice. This is indeed what tends to happen as the length of the corridors increase, or as conveyors become congested.

It is difficult to decide which of the above Logit models should be used preferably as a basis for any general conclusions about moving walkway utilization. However, the utility functions resulting from each analysis suggest that the travel speed model may be more sensitive to passenger related issues, such as passengers' ages or number of bags toted. Conversely, the relatively high alternative specific constants of the travel time model may better describe mode choice probabilities derived from the inherent physical characteristics of the corridor environment itself.

Shortcomings to the Above Study

It is conceded that the above mode choice analysis does have its share of shortcomings. The most prevalent is the fact that the observation process itself led to a series of biases in the sample.

The fact that sampling was only performed on a Sunday afternoon in April most certainly resulted in a biased sampling of leisure passengers. An additional survey performed during a weekday morning or evening would provide a larger sample of business passengers. It would be prudent to expand the data set to observations over different periods of a week, and perhaps a year, to collect a comprehensive, unbiased, and perhaps time-sensitive data set. In addition, the study may have included several "leisure" passengers who were not passengers at all, but those meeting or seeing off passengers. These people may have behavior patters of their own, which were not recognized in this study and merely were absorbed within the leisure passenger category. Furthermore, observer biases of a passenger's age and travel type are in no way insignificant. A direct response from the passengers themselves would alleviate any prejudices by the observers.

Some elements of the conveyor environment related to the physical environment and to the passenger characteristics were excluded from the survey. Environmental characteristics such as the presence of windows or other displays, or the presence of destinations (such as gates, or other corridors) at locations between the start and end of the conveyor were considered. Passenger group characteristics were also excluded. That is, there is no differentiation between a passenger traversing the corridor alone with one partner, or with a large group, etc. These characteristics are perhaps significant contributors to mode choice in the corridor.

COMPARISON WITH HEATHROW AIRPORT "TRAVELLATOR" STUDY

A study conducted by the Loughborough University of Technology assessed the use of the "travellator" passenger conveyor at London's Heathrow airport terminal 3 in April 1974 (*5*). The purpose of the study was to determine user behavior on the conveyors, much like this study. Their study, however, focused on safety and comfort issues concerning the conveyors. The findings of the study may have resulted in modifications to the design of passenger conveyors, including those at San Francisco's airport.

A preliminary study of user behavior at Heathrow revealed that a significant proportion (nearly 20 percent) of conveyor users had a non-negligible amount of difficulty with the conveyor. Most difficulties related to users losing their balance when boarding or alighting the belt. The loss of balance was primarily due to slight movements or compulsive jerks experienced when boarding. The results of the preliminary study led to a more in depth analysis of the travellator at Heathrow and a comparison to a similar conveyor in France (the Montparnasse travellator).

The Heathrow travellator ran for a length of 110 m in a corridor known as the "pier connector" that connects Heathrow's main terminal with "terminal 3." The conveyors were 1 m wide and were operated at a speed of 0.67 m/sec. Observations of passengers using the conveyor were made by filming pedestrian flows between 6:00 a.m. and 10:00 a.m. This time was chosen to observe peak flows, when large aircraft normally arrive from overseas. Using the film a total of 290 passengers were studied. Similar to our study, the sex, age, and number of bags carried by each passenger were recorded. Furthermore, the approach speed, step length, and boarding speed of each passenger were calculated (by counting travel distance per frame of film); whether the passenger used the conveyor handrail, did a "threshold check" (i.e., adjusted their step length to board the conveyor), and whether the passenger had any problems boarding were all noted.

The studies performed at Heathrow and Montparnasse found that the Heathrow conveyor had considerably more boarding problems (31 percent of sample) than the Montparnasse (20 percent) conveyor. This despite the fact that the Montparnasse conveyor traveled at a higher velocity (0.854 m/sec) than Heathrow's (0.67 m/sec).

The results of the study concluded that the main factor causing conveyor boarding problems was "improper boarding techniques." These techniques mainly involved "over-preparing" to board the conveyor, by altering one's step, grasping for the handrail too early, or looking down when boarding. Their conclusions were supported by the fact that the population of users at Montparnasse were younger, business travelers who were familiar with the travellator, whereas the Heathrow users were older, leisure passengers with less experience on moving walkways.

Whether the Loughborough conclusions are plausible or not, some of its recommendations for conveyor improvement appear to have been used in modern conveyor systems, including those in San Francisco International. For instance, the moving handrail was determined to be an important aid in maintaining one's balance when boarding the conveyor. Extending the handrail beyond the entrance threshold would help passengers to judge the speed of the system so that boarding could be accomplished more successfully. The width of the conveyor was determined to affect the ease of use as well. Conveyors that were too narrow often led to easily obstructed passageways, leaving less sight and, hence, less preparation for boarding. The study suggested that the width of the conveyor be increased to at least 1 m. Finally, the addition of instructional signs such as "Keep Walking when Boarding" were suggested.

The study suggested that these improvements along with the increased experience the public has with passenger conveyor would reduce the amount of passenger difficulties. During the course of the SFO study, no passengers were observed to have any difficulty with the conveyors. Although there were no instructional signs evident, the handrails were extended from the entrance threshold, the conveyor was wider than the Heathrow travellator and, probably, the passengers observed were more familiar with moving walkways.

CONCLUSION

In the above analysis of pedestrian mode choices throughout the United Airlines terminal at San Francisco International, we hope to provide some insight into who uses passenger conveyors, how, and why. By looking at the characteristics of the corridors themselves and the passengers who traverse the corridors, discrete choice models based on travel times and travel speed were made. In addition, the phenomenon of passengers changing foot speed was studied briefly.

The results of the analysis, although questionable in their statistical significance, do provide some insight into the use of passenger-moving walkways. It is shown that the vast majority of passengers use the conveyors in some manner. Those who use them tend to WALK along with the conveyor belt, rather than STAND still. There are suggestive relationships among passenger characteristics, environmental characteristics, and mode choice. The analysis suggests that looking at a travel speed based model is recommended when analyzing mode choice on the basis of passenger characteristics and that a travel time-based model is preferred when looking at issues of the physical corridor environment itself.

The above results lead to the implication that the passenger conveyor has become a popular mode of transportation not by reducing passenger travel time, but by acting as a convenience for those passengers who wish to slow their walking pace or stand still while traveling the corridor. For this reason, moving walkways have found a solid niche in airports for those routes with insufficient pedestrian density to warrant other modes, such as APMs, but sufficient lengths to preclude walking. Since the Heathrow study, moving sidewalks have appeared in more locations and have been improved, and as a result the public seems to be comfortable with their use. However, because moving walkways are perceived presently as a convenience rather than a necessity, their full potential may not be realized fully. It would be beneficial to passengers if moving walkway systems were developed that could capitalize on the low cost and convenience of use without having to pay the price currently associated with the mode's shortfalls, such as slow belt speeds, narrow belt widths, and one-destination limitations. Airport terminals would serve as excellent test-beds for conveyor improvements in the above areas. Terminals have a continual supply of unfamiliar system users. Also, systems easily can be tested in a short-distance configuration before full-scale installation. This ideal situation should encourage terminal designers to research any new developments in the moving walkway arena and to consider seriously installing cutting-edge systems that could outperform current technology.

With the above methods described in this empirical study and the above technical considerations, authorities considering the installation or modification of airport corridors with passenger conveyor systems may gain further insight into their potential investments. Such insight may also lead to the proliferation of the passenger conveyor, or moving walkway, further into the realm of pedestrian transport.

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Characterization of Gate Location on Aircraft Runway Landing Roll Prediction and Airport Ground Networks Navigation

XIAOLING GU, ANTONIO A. TRANI, AND CAOYUAN ZHONG

This study presents an aircraft landing simulation and prediction model. The model uses simple aircraft kinematics coupled with individual parameters to describe the landing process. A multiobjective optimization and a shortest path algorithm are used to predict the aircraft exit choice and taxiway path in the runway taxiway network. By recognizing pilot motivation during the landing process, several influence factors such as terminal location, runway, and weather conditions are considered in the aircraft landing simulation. Random variables such as aircraft runway crossing height, flight path angle, approach speed, deceleration rate, and runway exit speed are generated to represent the stochastic landing behavior of aircraft by using a Monte Carlo sampling technique. With real-time input data, the model could provide information on aircraft exit choice, runway occupancy times, and shortest taxiway path to an assigned terminal location for both the pilot and the air traffic controller in a ground traffic automatic control system. This model can also be used to solve runway exit location problems by providing the expected distribution of aircraft landing distances and predict aircraft runway occupancy times. An interactive computer program has been developed on an IBM RISC 6000 workstation to perform these tasks.

With the increase in air traffic demands, airport ground network operation analysis becomes more important to fully realize the capacity of airports. The use of new Air Traffic Control System (ATC) technologies in the near future could reduce the aircraft in trail separations in the airport terminal area thus making aircraft runway occupancy times become an important factor in determining airport capacity. The expected intensity of runway operations in the future will also influence the safety of these operations thus requiring more precise methods of determining aircraft state variables in real-time on a ground network. Landing aircraft processing is one of the key factors in airport ground network operation analysis. A better understanding of the aircraft landing process could help to improve airport ground operation management and the safety of aircraft operations. Furthermore, it could provide knowledge for ground network designs including the optimal runway exit location problem.

The Aircraft Landing Simulation and Prediction Model (ALSPM) described here has been calibrated using real aircraft landing data observed at five major airports in the United States. With real-time input data, this model could provide landing information instantly to both pilots and air traffic controllers in a ground traffic automatic control system. The information could include acceptable runway exits, the probability of each aircraft taking these exits, related runway occupancy times, and advisories on the shortest taxiway path to an assigned gate. The model described here can also provide information about the distribution of aircraft landing distance and runway occupancy times for determining optimal runway exit locations. This procedure is usually carried out in the planning stage of new runway facilities.

Department of Civil Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Va. 24060

BACKGROUND

Earliest efforts to describe aircraft runway landing process are found in runway exit optimization and capacity analysis (*1–3*). In 1974, Joline (*3*) used an aircraft deceleration model to predict the runway occupancy time in the runway exit location problem. Based on the aircraft landing data collected at Chicago's O'Hare airport, the model divided the landing process into three phases. Phase 1 accounts for the aircraft motion from threshold to the touchdown point with the vehicle flying at a constant speed profile. In phase 2 the aircraft uses a deceleration rate consistent with the use of reverse thrust until it reaches a coast speed. Phase 3 has two cases in which the aircraft either uses the deceleration rate in Phase 2 to reach an exit with the required turnoff speed (i.e., there is an exit located at that place) or the aircraft coasts for ΔT time and then uses the deceleration rate in Phase 2 to reach the exit with the required turnoff speed. This model does not consider any influence of airport layout and environmental factors such as the gate locations, runway grades, the weather conditions, and so on, which may cause significant deviations in aircraft landing operations at different airports.

Several empirical studies on aircraft landing behaviors were conducted in the late 1970s (*4,5*). Through analysis of observations collected at different airports, Koenig (*4*) found that a key factor influencing the aircraft selection of an exit is the terminal gate location. Other factors such as the traffic density, passenger comfort, and so on, also have influence on the landing performance. He found that pilots in many instances have the motivation to exit early in order to reach their assigned gate in shorter times. He pointed that this motivation factor could be used to reduce runway occupancy times.

In 1990, Ruhl (*6*) presented an aircraft landing model which uses aircraft individual parameters to predict the aircraft runway occupancy time. In this model, aircraft runway landing operations are divided into five segments. In Phase 1 the aircraft crosses the threshold and travels at a constant speed until a flare maneuver is initiated. Phase 2 encompasses the flare maneuver and ends when the main gear touches down. Phase 3 starts from the point where the main gear touches down until the nose gear impacts the ground. Phase 4 starts at the nose gear touchdown point with the aircraft speed bleeding off at an average braking deceleration rate until reaching a suitable exit. It is assumed here that if the deceleration rate under normal conditions allows the aircraft to accept an exit (means the aircraft could decelerate to the required speed before it reaches the exit) the pilot will adjust (decrease) the deceleration rate to meet the required exit speed at the time the aircraft reaches the exit. Phase 5 starts at the point the aircraft begins to turn off on the runway until it clears the runway. One shortcoming in this model is the obvious simplification of the aircraft deceleration phase (Phase 4). According to our observations, pilots use different strategies in this phase based on the exit location. For example, an aircraft may decelerate to a certain speed and coast for some time and decelerate again to reach its exit. Simplifications in this phase usually result in higher runway occupancy times than those observed in the field. Another problem is that there is no inclusion of motivational factors in this model. Ruhl mentioned the influence of the terminal location to the aircraft landing operation in his paper. However, the model did not consider this factor (*6*).

Another aircraft landing simulation model was developed to estimate aircraft runway occupancy time for runway exit location and runway occupancy time minimization at Virginia Polytechnic Institute (*7*). This model also divided the landing process into five phases including a flare phase, two free roll (or transition) phases, a braking phase, and a turnoff phase as shown in Figure 1. Several random variables, such as the approach speed, aircraft landing weight factor, and the deceleration rate during the braking phase, are generated using a Monte Carlo sampling technique. Factors that have influence on the aircraft landing operation are included in this model, such as weather conditions and the local effect of runway grades. Runway length as a pilot motivation factor is also considered and a more realistic braking phase related to the aircraft exit choice is used. However, the gate location influence was not considered to simplify the complexity associated with a runway exit optimization model and its portability on a personal computer (*7,8*).

This study addresses some of the limitations of previous models and describes a technique to predict landing roll performance in realistic airport operational conditions considering gate location as a causal factor in the exit choice model.

MODEL DEVELOPMENT

Based on the five-phase aircraft landing process shown in Figure 1, the model uses Monte Carlo simulation to perform 250 trails for each landing aircraft. Motivation factors, runway, and weather conditions factors are considered in the simulation to represent different airport environments. The most important improvement in this model is the consideration of the gate location as a motivation factor. A multi-objective optimization method is implemented here to link this factor to the aircraft landing performance and exit choice. The model describes the aircraft landing roll performance based on the consideration of a complete ground network. This provides more realistic results which could be used in automatic ground control system development and runway exit location optimization procedures.

Aircraft Landing Process Description

The aircraft landing process is broken down into five phases: flare phase, first free roll phase, braking phase, second free roll phase, and turnoff phase as illustrated in Figure 1.

The flare phase starts from runway threshold until the aircraft touches down. The landing distance, S_{air}, and travel time, t_{air}, are estimated by Equations 1 and 2 under the assumption that the aircraft uses a steady descent flight path angle g (3.0° typical) with a constant nominal acceleration during the flare maneuver at 1.2 g's (*9,10*).

$$S_{air} = \frac{h_{th}}{\gamma} + \frac{V_{fl}^2}{2g(n_{fl} - 1)} + \Delta S(rl) \tag{1}$$

$$t_{air} = \frac{2S_{air}}{V_{ap} + V_{td}} \tag{2}$$

where

h_{th} = threshold crossing height,
V_{fl} = flare speed,
n_{fl} = flare load factor,
$\Delta S(rl)$ = adjustment distance of S_{air} according to different runway length (rl),
V_{ap} = aircraft approach speed, and
V_{td} = touchdown speed.

The first free roll phase starts at the point where the main gear touches down and ends when thrust reverses and braking are

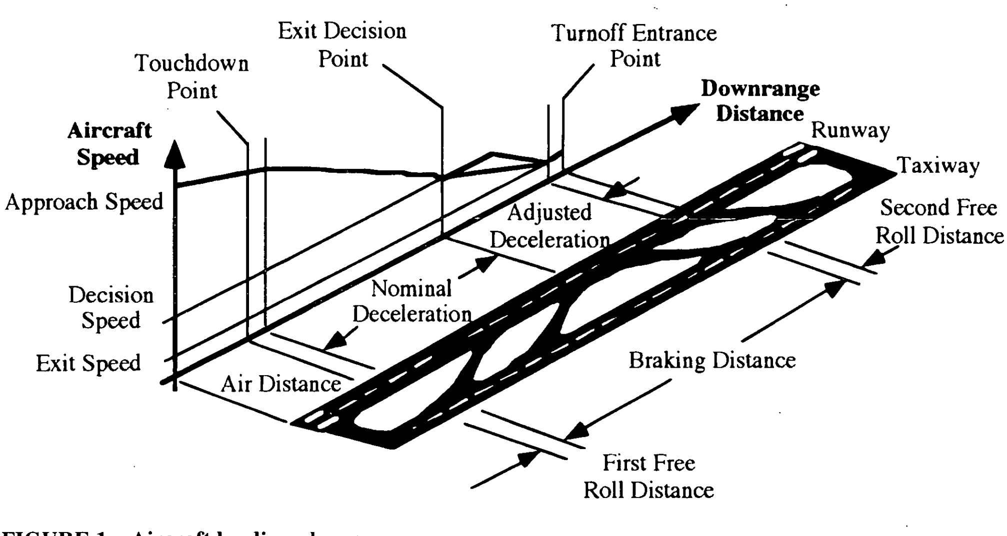

FIGURE 1 Aircraft landing phases.

applied. It is assumed that aircraft travels at a constant speed for about 1–2 sec.

$$S_{fr1} = V_{td} \times t_1 \quad (3)$$

where S_{fr1} is the first free roll distance, and t_1 is the travel time.

The braking phase starts from the ending point of the first free roll phase until the aircraft decelerates to an acceptable exit design speed (V_{ex}). The aircraft uses a nominal deceleration rate to decelerate to a speed called decision speed (V_{des}). The model checks for a possible coasting distance (S_{coast}), under the assumption that the aircraft uses the nominal deceleration rate to reach the selected exit after coasting. If this distance is within certain range (l_{dec}), the aircraft uses the adjusted deceleration rate to reach the exit's design speed without coasting. If the distance exceeds l_{dec}, the aircraft coasts for some time under the decision speed and then uses the nominal deceleration rate to decelerate to the exit. The nominal deceleration rate (dec), is calculated considering the manufacturer's published landing distance and subtracting an air distance (*7*). It is also adjusted by runway local gradient, surface conditions (wet or dry), aircraft landing weight information and the aircraft assigned gate location. The decision speed used in the model has been obtained through empirical data collected at various airports (*11*). Equations 4 and 5 are used to estimate the braking phase distance (S_{br}) and time (t_{br}).

$$S_{br} = l_{ex} - (S_{air} + S_{fr1} + S_{fr2}) \quad (4)$$

$$t_{br} = \begin{cases} 2 \times \dfrac{S_{br} - \dfrac{V^2_{td} - V^2_{dec}}{2 \times dec}}{V_{dec} + V_{ex}} + \dfrac{V_{td} + V_{dec}}{dec} & \text{if } S_{coast} < l_{dec} \\ \dfrac{V_{td} - V_{dec}}{dec} + \dfrac{S_{br} - \dfrac{V^2_{td} - V^2_{ex}}{2 \times dec}}{V_{dec}} & \text{if } S_{coast} \geq l_{dec} \end{cases} \quad (5)$$

where l_{ex} is the distance from a selected exit to the runway threshold, and S_{coast} is the possible coasting distance which can be calculated by using Equation 6.

$$S_{coast} = l_{ex} - \left(S_{air} + S_{fr1} + S_{fr2} + \frac{v^2_{td} - v^2_{ex}}{2 \times dec}\right) \quad (6)$$

An exit choice model is used in the braking phase to determine the most likely exit to be used. This model will be described later.

The second free roll phase is scheduled after the braking phase just before the aircraft starts turning off from the runway. This phase is associated with the pilot identification and decision procedure to take a specific exit. The aircraft will travel at a constant speed (i.e., the exit speed) for about 1–3 sec.

$$S_{fr2} = V_{ex} \times t_1 \quad (7)$$

where

S_{fr2} = second free roll distance,
t_2 = travel time, and
V_{ex} = exit speed.

The turnoff phase is used to describe aircraft exit turnoff behavior and estimate the turnoff time. This phase starts from the point where aircraft begins the turnoff maneuver and ends at the point where the aircraft clears the runway. The turnoff time (t_{tof}) is estimated through numerical integration using a 4th order Rung-Kutta algorithm (*12*) as shown in Equation 8.

$$t_{tof} = f(V_{ex}, b_{tail}, b_{wing}, R_w, ET) \quad (8)$$

where

b_{tail} = aircraft tail plane span,
b_{wing} = aircraft wing span,
R_w = runway width, and
ET = selected exit type.

As described above, the aircraft runway occupancy time ROT can be estimated by adding all individual times in all phases.

$$ROT = t_{air} + t_1 + t_{br} + t_2 + t_{tof} \quad (9)$$

Figure 2 shows two Boeing 727-200 landing simulation trajectories to illustrate differences in landing roll behavior at two hypothetical runway exit locations.

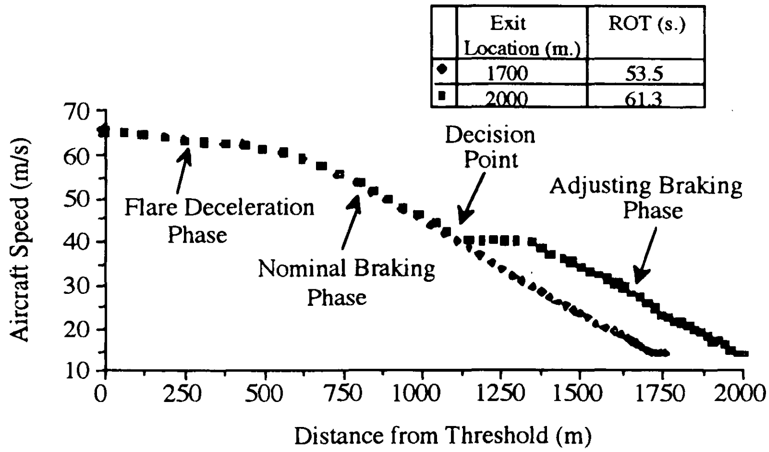

FIGURE 2 Sample velocity profiles (Boeing 727-200).

Aircraft Stochastic Landing Behavior

Monte Carlo sampling technique is used in runway landing simulation to represent the stochastic behavior of landing aircraft. Created random variables include aircraft landing weight factor (w_f) (*7*), runway crossing height (h_{th}), flight path angle (γ), flare speed (V_{fl}), deceleration rate in braking phase (dec), and exit speed (V_{ex}). All of these random variables are assumed to have normal distributions as shown in Equation 10.

$$X \sim N(\mu, \sigma) \tag{10}$$

where

X = random variable,
μ = mean value, and
σ = standard deviation.

The upper and lower boundary values are set for each distribution according to the landing observation analysis carried out by the Virginia Polytechnic Institute Transportation System Laboratory at five east-coast airports (*11*).

Terminal Location Influence on Landing Process

The terminal location is known to have influence on the aircraft runway landing behavior (*4,6,11*). In this model, two strategies are used to reflect this influence.

Strategy 1

If under the nominal deceleration rate an aircraft passes over the perpendicular plane of the terminal location, a more aggressive deceleration rate is used by the model to reflect the pilot's motivation for attempting an earlier exit.

$$\text{dec} = \begin{cases} \text{dec}_{\text{nor}} & \text{if } \; lr < f(GL) \\ (1+\lambda) \times \text{dec}_{\text{nor}} & \text{if } \; lr \geq f(GL) \end{cases} \tag{10}$$

where

dec_{nor} = nominal decoration rate,
γ = landing motivation factor,
lr = aircraft nominal landing distance, and
$f(GL)$ = function of terminal location GL.

Figures 3 and 4 show Boeing 727-200 landing distributions (to a speed of 15 m/sec) simulated by the model for two values of the landing motivation factor. The terminal location for this example is assumed to be near the active runway threshold (i.e., pilots could be heavily motivated to shorten their landing rolls to reach the terminal location).

Strategy 2

The shortest aircraft taxiing time to the terminal location is used as a factor to influence aircraft exit choice. It is assumed that the landing aircraft will choose the acceptable exit which can minimize its runway occupancy time plus its weighted shortest taxiing time (see Exit Choice Model in detail).

The Exit Choice Model

A multiobjective integer optimization model is developed to find the exit for landing aircraft. Minimizing the aircraft runway occupancy time (*ROT*) and minimizing taxiing time (*TT*) are the two objectives. A taxiing time weight factor is used to combine these two objectives. The following two assumptions are made in the model: 1) The landing aircraft will choose the acceptable exit which can minimize its *ROT* plus its weighted *TT*. 2) The aircraft *ROT* is at least equally important with *TT*. This fact is used to achieve a balance between individual and collective (system wide service times). The model can be described mathematically as follows:

$$\text{Minimize} \sum_{i=1}^{n} (ROT_{ik} + wf_k + TT_{ik})x_i$$

$$\text{Subject to} \sum_{i=1}^{n} x_i = 1 \tag{11}$$

$$l_{ex}(i) \geq S_{air} + S_{fr1} + S_{fr2} + S_{br}$$

$$x_i = 0 \text{ or } 1$$

$$i = 1, \ldots, n \text{ and } k = 1, \ldots, m$$

where

i = runway exit index number,
n = total number of exits,
$l_{ex}(i)$ = location of the ith exit,
k = terminal index,

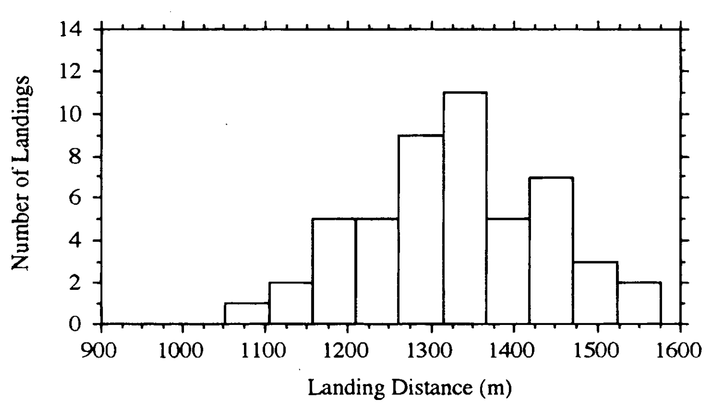

FIGURE 3 Boeing 727-200 landing distribution (λ = 0).

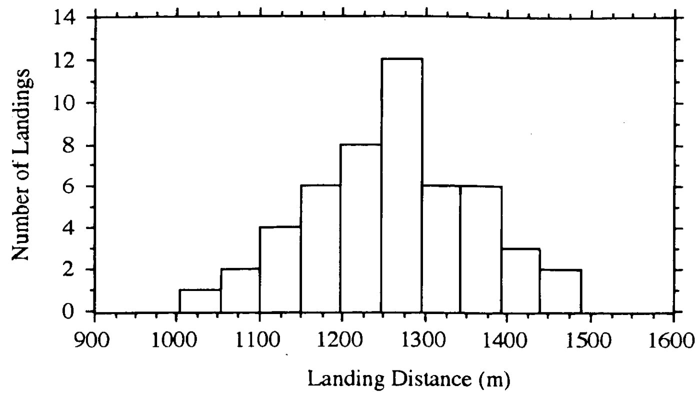

FIGURE 4 Boeing 727-200 landing distribution ($\lambda = 0.1$).

wf_k = taxing time weight factor for airline k, and
x_i = binary variable which indicates the aircraft will either take exit i (1) or not (0).

Since the number of runway exits is limited, we use a numerical method to solve this integer program problem. The determination of wf_k will be discussed in following section.

Taxiing Time and Taxiway Path Prediction

The aircraft shortest taxing time and taxiway path can be estimated by solving the following shortest path optimization model.

Suppose we have a taxiway network G with m nodes, n arcs, and a cost c_{ij} associated with each arc (i, j) in G. The shortest path problem is to find the least costly path (i.e., shortest path) from node i to node j.

The mathematical description is to find the shortest path from node l to node k:

$$\text{Minimize} \sum_{i=1}^{m} \sum_{j=1}^{m} c_{ij}x_{ij}$$

$$\text{Subject to} \sum_{j=1}^{m} x_{ij} - \sum_{k=1}^{m} x_{ki} = \begin{cases} 1 \text{ if } i = l \\ 0 \text{ if } i \neq l \text{ or } k \\ -1 \text{ if } i = k \end{cases} \quad (12)$$

$$x_{ij} = 0 \text{ or } 1$$
$$i, j = 1, \ldots, m$$

where x_{ij} is a binary variable which indicates arc (i, j) is either in the path (1) or not (0), and c_{ij} is the travel time that the aircraft spends on link (i, j). To simplify this model at this stage we assume that the aircraft taxiing speed is constant on each taxiway link.

Procedures in Landing Simulation and Prediction

The landing simulation and prediction include following steps:

1. Airport environmental data input: these data include information on runway and taxiway network, the prevailing airport weather condition, and terminal locations.
2. Taxiing time weight factor determination: to calibrate wf_k, aircraft landing roll data should be collected and analyzed. Running the model for different values of taxiing time weight factor wf_k, and comparing the results with field data, we can find the best suitable taxiing time weight factor.
3. Aircraft landing simulation: two hundred and fifty landings are generated using a Monte Carlo sampling technique. The model generates random trajectories according to variations in the runway crossing height, flight path angle, landing weight factor, aircraft deceleration rate, and exit speed. Each landing follows the five landing phases described before.
4. Simulation results: by sorting the simulation results of each landing and recalculation, the model will provide the exit choice probabilities to each exit, runway occupancy times, and the shortest taxiway path.

APPLICATION

Operations at Washington National Airport have been studied to test the validity of this model. This airport has also been used to see the possible effect of terminal location on landing roll performance. Based on this application, sensitivity analysis has been done by changing the terminal location and the value of taxing time weight factor.

As mentioned before, the model could also be used in a ground traffic automatic control system. With real-time information such as the aircraft approach speed and the touchdown distance which could be provided by airport radar system or on board equipment, the model could serve as an advisory system to pilots and air traffic control personnel to automate the aircraft runway exit choice and find the shortest path to an assigned gate thus saving fuel and minimizing runway occupancy times. Model predictions with known approach speed (i.e., extracted from radar or differential GPS transmitters) could also reduce the standard deviation of runway occupancy times thus contributing to a better utilization of runway infrastructure.

1. Case Study

We used runway 36 at the Washington National Airport as an example to test the proposed model. The length of this runway is 2040 meters and the runway exit information is shown in Table 1.

Figure 5 shows the runways and related taxiway network at this airport. Landing events for USAir Boeing 737-300 aircraft are predicted and compared with field observations collected at the airport. The selection of one airline and one aircraft model is made to narrow the scope of the possible correlation of parameters in the model.

TABLE 1 Runway 36 Exit Information

Exit Name	Exit Type	Location From Threshold (m)	Exit Speed (m/s)
G	Pseudo 90 Deg.	950	10
H	Pseudo 45 Deg.	1025	15
I	45 Deg.	1325	15
RWY	Pseudo 30 Deg.	1470	18
J	90 Deg.	2040	10

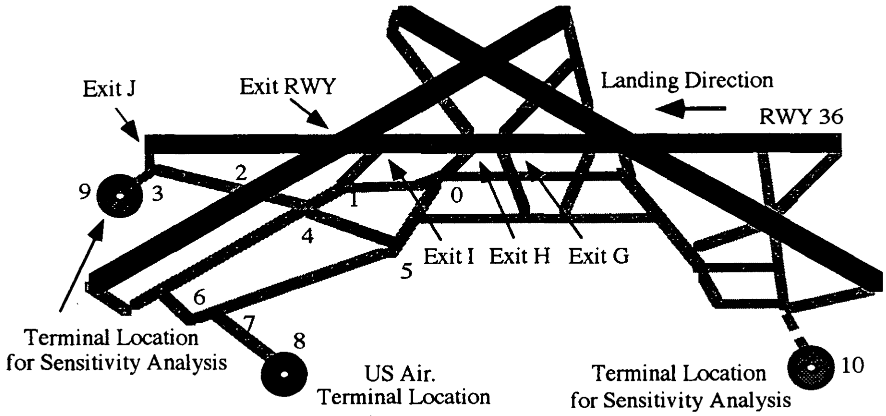

FIGURE 5 The ground network of Washington National Airport.

The USAir terminal is also particularly suitable in this analysis because its location is near the end of runway 36.

Preliminary analysis of 36 observed Boeing 737-300 landings found that the most suitable taxiing time weight factor for this aircraft/runway combination to be 0.4. Figure 6 shows the exit choice predictions and the observed exit choice distribution. Figure 7 shows the runway occupancy time prediction and the observed values. Note that in both cases there is good agreement between predicted and observed values.

The model prediction is sensitive to the airline terminal location. Hypothesizing different terminal locations (indicated as nodes 9 and 10 in Figure 5) and using the same taxiing time weight factor (0.4), we have the different predictive results. Figure 8 shows the exit choice predictions for three different terminal locations.

It is obvious that the taxiing time weight factor has no influence on the landing predictions when the terminal location is at Node 10. This is because minimizing the aircraft runway occupancy time will minimize the aircraft taxiing time automatically in the exit choice model. In this case the difference is attributed to changes in the landing motivation factor. Landing aircraft use more aggressive deceleration behavior in the braking phase.

The model predictions are also sensitive to the value of taxiing time weight factor. Figure 9 shows the exit choice predictions under different taxiing time weight factor values (with the terminal loca-

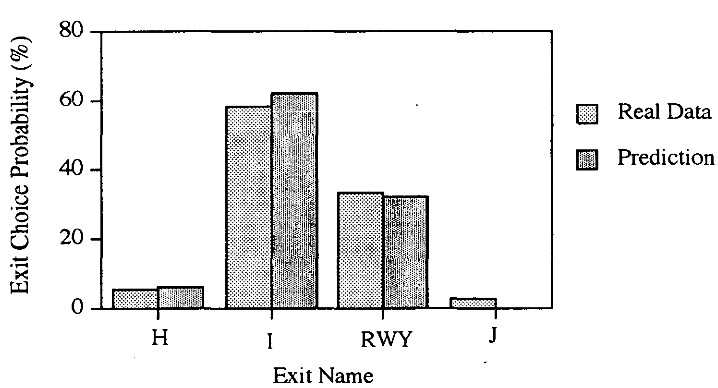

FIGURE 6 Exit choice observation and prediction.

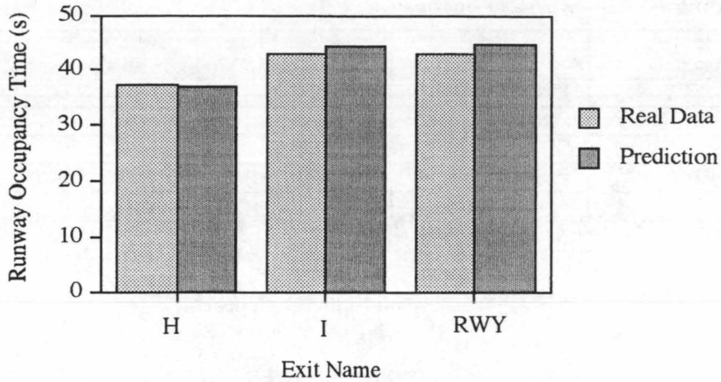

FIGURE 7 Runway occupancy times observations and predictions.

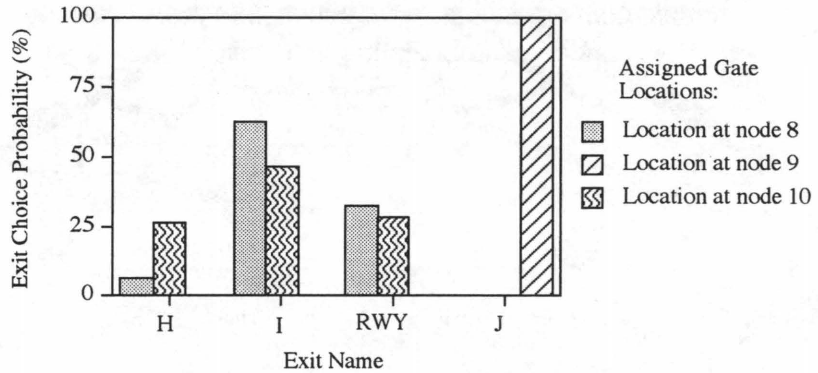

FIGURE 8 Influence of terminal location on exit choice probability.

tion at Node 8). We can see that the landing aircraft will have a tendency to take the exits closer to the terminal when the taxiing time weight factor is increased. This is representative of motivated pilots who are willing to trade off some runway occupancy time (*ROT*) for taxiing time. This fact, when taken to an extreme, could affect the runway acceptance rate due to longer *ROT* values.

2. Prediction With Real-Time Data

With real-time data updates this model could provide more accurate predictions. Automated updates could come in the form of aircraft state variable information extracted from aircraft surveillance radar data or information download from on-board navigation equipment and differential position sensors on the ground. Figure 10 shows the expected landing distribution for Boeing 737-300 aircraft with no real-time update data. Figure 11 shows the landing distribution with known approach speeds (55 m/sec) and touchdown point location (450 m). We can see from these two figures that with more information the aircraft landing behavior tends to be more predictable and the resultant dispersion of runway occupancy times could result in slightly higher runway acceptance rates. This could prove to be useful if in-trail separations under Instrument Meteorological Conditions (IMC) are reduced further from current values as the mag-

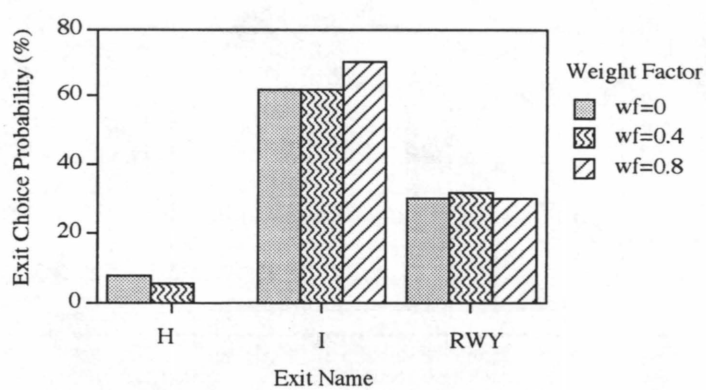

FIGURE 9 Influence of taxiing weight factor.

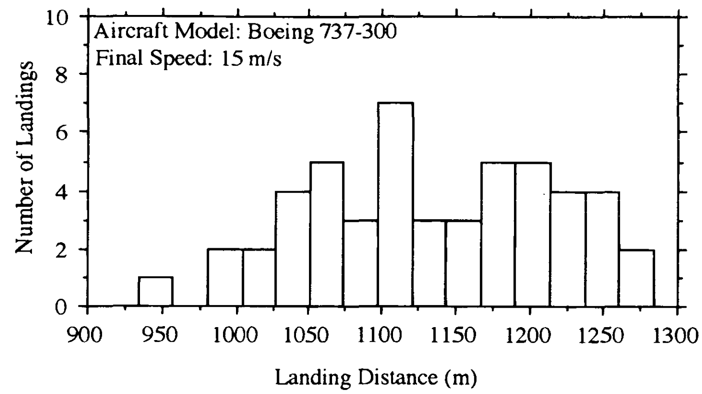

FIGURE 10 Landing distributions with no real-time update data.

nitude of runway occupancy times will be closer to in-trail separation. Also, under current Visual Meteorological Conditions (VMC) with heavy banks of flights, a reduction in the mean and standard deviation of *ROT* could enhance the safety of operations by increasing the gaps between successive arrivals.

CONCLUSIONS AND FURTHER RESEARCH

The preliminary results presented in this study indicate that the model described provides a more realistic way to analyze landing aircraft behaviors in complete airport ground networks. The use of individual aircraft parameters and a calibrated model using observed landing data made the analysis more accurate. The most important improvement in this model is the consideration of terminal location influence on landing behavior. This consideration makes it possible to explain the aircraft landing roll phenomena consistent with a particular ground network with more accuracy.

Providing landing predictions to the pilot and air traffic controller in the ground traffic control system, the model could help to solve ground network traffic congestion problems and enhance operational safety. The model results could also be used in the runway exit location problem to increase runway capacity.

Further studies are needed to improve the model prediction capability, including the influence of traffic density on aircraft landing behavior, the determination of landing motivation factor for a multitude of airport/aircraft combinations, and their associated taxiing time weight factors. Also, the development of a time dependent traffic assignment algorithm would help in the predictions for an advanced ground control ATC system.

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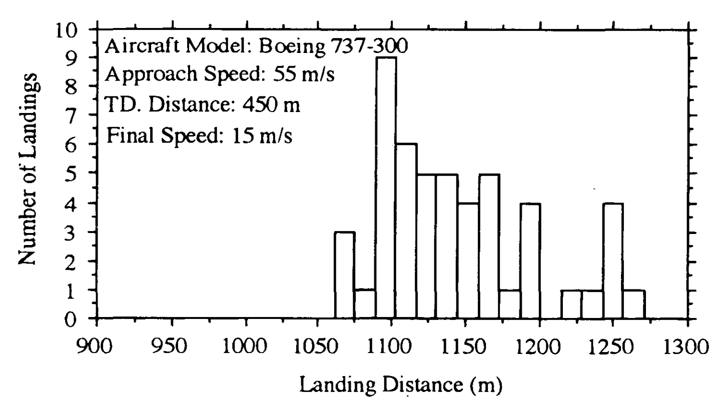

FIGURE 11 Landing distributions with known approach speed and touchdown distance.

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Economic Characteristics of Multiple Vehicle Delivery Tours Satisfying Time Constraints

MAX K. KIESLING AND MARK M. HANSEN

Since deregulation of the aviation industry, a substantial body of literature has emerged analyzing the economic structure of passenger carrier operations. By comparison, a paucity of literature exists that addresses the economics of air freight transportation. This study contributes to filling that void by assessing the economic structure of ground-side freight distribution for air express carriers. To do so, we develop an "engineering" cost model of the ground-side distribution process. This circumvents the problem that appropriate historical performance data is not available with which to develop an "economic" cost model and affords greater flexibility and accuracy than the more frequently applied econometric based cost models. The cost model is developed by first employing a mathematical heuristic to design and locate freight delivery subregions employed by freight carriers operating under time constraints. The results of the design heuristic are then used to create a model that incorporates costs of overcoming distance, stopping costs, marginal freight distribution costs, and fixed vehicle costs. It is then used to demonstrate that ground-side freight distribution operations exhibit significant economies of scale and profound economies of density. Furthermore, it is indicated that increasing the delivery time constraint decreases distribution costs. However, this decrease in costs must be tempered with the trade-off that increasing the delivery time constraint could decrease the market available to the carrier.

The air cargo industry was deregulated in November 1977, 1 year before deregulation of the passenger airline industry. At that time, air cargo was primarily transported in the bellies of passenger aircraft with the notable exception of the cargo transported by Flying Tigers, a successful international air freight forwarder. Door-to-door delivery was uncommon, and overnight delivery was the exception, not the norm.

The industry changed dramatically after deregulation, as Federal Express Corporation, a small package express carrier, emerged and rapidly grew to dominate the air freight industry. Federal Express' rapid growth eventually led to their purchase of Flying Tigers [see Sigafoos (*1*) and Trimble (*2*)]. Attracted by Federal Express' rapid rise to dominance and success, several other specialized air freight carriers emerged including UPS, Airborne Express, and DHL. By the mid-1980s the air cargo industry was dominated by these service oriented carriers, forming the organizational structure that exists today in the aviation industry: specialized carriers that focus on either cargo or passenger transportation.

One factor contributing to the rapid rise of dedicated air freight carriers was the apathy of passenger carriers toward air cargo following deregulation. However, there is reason to believe that the passenger carriers' apathy has ended. Shaw (*3*) reports that five major U.S. passenger carriers (American Airlines, Delta Air Lines, Northwest Airlines, United Airlines, and USAir) have joined forces with Roadway Package System (RPS), a national ground carrier, to provide door-to-door delivery of freight and compete with integrated freight carriers. Such an alliance has far-reaching implications. If passenger carriers can effectively compete with dedicated freight carriers, there will be a continued need for joint-use airports (i.e., both freight and passenger carriers using the same airports). If they cannot compete, there will be an increased specialization of services (specializing either in freight or passenger transportation) and, consequently, an increased need for specialized airports.

To assess how competitive dedicated freight carriers and combination carriers can be (from an economic perspective), we must be able to quantify the operational cost of freight delivery. One accepted way to do this is to develop an "economic" cost model using industrywide or carrier specific data to calibrate econometric cost and/or production functions [Kiesling and Hansen (*4*)]. Unfortunately, data are very limited, particularly for dedicated freight carriers and for specific delivery operations such as ground-side distribution, to support such an analysis. As a result, we employ another possible approach, which is to develop an "engineering" cost model of the more specific operations of air freight carriers. The results presented in this paper are the first step in developing such a model. (Whereas the final goal is to develop engineering cost models of system-wide operations, this study addresses only ground-side transportation costs.)

Ground-side pickup and delivery operations are a crucial battleground in the competition between specialized and combination freight carriers. One reason is that pickup and delivery operations are the interface wherein customers judge the level of service received. As delivery deadlines attest, one critical factor in defining the level of service is time. Air express customers pay premium rates for the timely transport of goods, both in the sense that pickup and delivery deadlines are reliably met, and in the more general sense that freight can be delivered as early as possible in the business day and be picked up as late as possible in the business day. The determination of pickup and delivery deadlines is one decision variable that effects the level of service provided. As will be indicated in this report, however, it is also a decision variable that significantly effects the costs incurred by the freight carrier—shorter time constraints raise the operational costs to the carrier. This trade-off will prove to be a crucial element in the competition between freight carriers.

The design and operation of multiple-vehicle delivery systems (such as those described above) have been analyzed by numerous authors. Daganzo (*5*) explores the impact that zone shape has on tour building strategies and ultimately on tour lengths. Daganzo (*6*) presents a strategy for designing distribution problems in which N

The University of California at Berkeley, Institute of Transportation Studies, 107A McLaughlin Hall, Berkeley, Ca. 94720-1720.

points must be visited by a fleet of vehicles operating under the constraint of a maximum of C stops per vehicle. Newell and Daganzo (*7,8*) expand this work further by considering larger delivery areas wherein line-haul distances are significantly greater than local travel distances. Newell (*9*) modifies the analysis to consider the movement of valuable goods. In all of the above studies, vehicles are constrained by capacity. Relatively little has been done on the design of multiple vehicle delivery systems constrained by time. One such study, by Langevin and Soumis (*10*), does consider this problem, but only for ring-radial networks and a centrally located depot. Han (*11*) also focuses primarily on ring-radial networks in developing routing strategies for multiple vehicle delivery problems.

This study explores the design of multiple-vehicle delivery systems constrained by time (not vehicle capacity or dispatch frequency), and applies the design process to several different types of cities. Section 1 presents the basic distribution process that is employed by air freight carriers, and defines the basic design problem. Section 2 applies the design process to linear cities and cities with L_1 metrics. Section 3 discusses the impact of "fast roads" on the design of delivery subregions, and extends the design process to allow for fast roads. Section 4 uses the results from Sections 1–3 to estimate the average unit cost of transporting freight on the ground-side distribution system, and demonstrates the crucial role that pickup and delivery time constraints play in ground-side distribution.

MINIMIZING DELIVERY COSTS

Simply stated, the air freight carrier's goal in designing its ground-side distribution system is to visit all pickup and delivery points in the city at minimal cost. Two constraints determine how many vehicles are required to accomplish this task. First, vehicle weight and volume constraints are likely exceeded before all points in a city can be visited, even in small cities. It follows that the next best solution is to fully use delivery vehicles by visiting as many points as possible before weighing-out (meeting the vehicle's weight limit) or cubing-out (meeting the vehicle's volume limit). However, the time-sensitive nature of delivery deadlines precludes the vehicles from even visiting enough points to reach vehicle capacity, meaning that *time* is the second, and as it turns out the binding, design constraint. The solution is to divide the delivery area into subregions, the size of which are determined by the maximum number of points that a single delivery vehicle can visit in the allotted time. This is equivalent to minimizing the number of delivery subregions in the delivery area.

To illustrate analytically, consider the following simplified ground-side delivery cost function facing a freight carrier:

$$TC \approx dC_d + T_l C_l + NC_v \quad (1)$$

where

C_d = cost per mile traveled,
C_l = cost per hour of labor, and
C_v = fixed cost per vehicle.

First, consider the cost per distance term of Equation 1. Let N be the number of delivery subregions required to visit all pickup and delivery points, n, in a city. Each delivery tour consists of a line-haul portion (the distance from the terminal to the nearest point in the tour), and a local travel portion (the distance required to visit all pickup and delivery points in the subregion). For a given number of pickup and delivery points in a city, increasing N by one increases the total line-haul distance traveled by an amount on the order of the average distance from the terminal to all pickup and delivery points in the city. However, it decreases the total local distance traveled by approximately the average travel distance between pickup and delivery points. Because line-haul trips are almost always much longer than the average distance between pickup and delivery points, it follows that the total travel distance increases with N. Thus, to minimize the cost of overcoming distance, we would want to minimize N.

The relationship between N and the labor cost of delivery follows a similar vein. Let T_l be the total labor (hours) required to service all pickup and delivery points in the city, which is comprised of the total time required to travel (both line-haul and local travel) and the total time required to handle and process freight at each pickup and delivery point. The latter is constant regardless of the size of N. Since the total travel time is directly proportional to the total distance traveled, it is obvious that the total travel time also increases with N. Thus, the labor costs are comprised of fixed and variable (with N) components, which are minimized by minimizing N.

Finally, it is clear that if one delivery vehicle is assigned to each subregion, the vehicle cost is also minimized by minimizing N. These transformations allow the cost function to be rewritten:

$$TC \approx f_1(N)C_d + f_2(N)C_l + NC_v \quad (2)$$

where $f_i'(N) \geq 0$. Therefore, to minimize costs, carriers should minimize the number of delivery subregions required, subject to the constraint that all points are visited in time T.

DESIGN OF MULTIVEHICLE DELIVERY ZONES

Designing delivery subregions is a detailed, and case specific, activity. Results differ with changes in the terminal location or the underlying transportation metric. The design process remains the same, however, as formalized below.

Let T be the amount of time allotted to visit all points in the delivery area (city). Only one delivery vehicle visits each subregion in time T. For the delivery process, T includes the time required to travel to the delivery subregion and visit all points in the subregion. For the pickup process, it includes the time to visit all points in the subregion and return to the terminal. (For cost estimating purposes, both line-haul trips must be included.)

We can analytically express the design constraint by defining three time quantities: the line-haul time, $T1$, which is time required to travel from/to the terminal to/from the delivery subregion; the handling time, $T2$, which is the time required to transport freight to/from the customer from/to the vehicle; and the local travel time, $T3$, which is the time required to travel the local streets between pickup and delivery points. The sum of these activities must be less than or equal to T for all delivery subregions:

$$T1 + T2 + T3 \leq T \quad (3)$$

This basic constraint holds true for all transportation metrics and city shapes analyzed in the remainder of this section, wherein several different scenarios are analyzed. For simplicity of demonstration, a linear city is analyzed first. The design process is then expanded and applied to cities with L_1 transportation metrics, a scenario that is much more realistic than linear or ring-radial cities. Finally, the impact of fast roads on the design of delivery subregions is considered, providing the most realistic design framework possible.

Linear City

To formalize and demonstrate the design process, a linear city of length D_C is considered first. A terminal is located at one end of the city, and all points to be visited are randomly distributed across its length. Delivery subregions are nonoverlapping zones of length d_i, located a distance D_i from the terminal, as shown in Figure 1. Subregions are located adjacent to one another, so that $\Sigma di = D_C$.

The line-haul time, $T1$, is the time required to travel between the terminal and the nearest edge of the subregion. By assuming an average velocity, v, the line-haul travel time to subregion i is simply $T1 = D_i/v$.

The handling time, $T2$, for a vehicle of the ith subregion is the time required to perform the delivery or pickup tasks at all points in the subregion. Such a task includes parking the vehicle, walking to the appropriate location, processing the required paper work, handling the package, and returning to the vehicle. To obtain the total handling time in subregion i, we assume that the handling time per stop, τ, is constant on the average, which we then multiply by the total number of points in the subregion. If δ is the customer density (number of points per unit length), then the expected number of points in subregion i is $\delta\, d_i$. Thus, the total handling time of zone i is $T2 = \delta d_i \tau$.

The third element of the time constraint is the local travel time, which is the time required to travel between all points in a specific zone. When the number of points in a subregion is sufficiently large, the distance traveled is closely approximated as the length of the subregion. If there are few points in the subregion, however, it may be deemed necessary to reduce the travel distance by one half the expected distance between points, $1/(2\delta)$. Assuming there is a sufficiently large number of points in the subregion, the local travel time in subregion i is $T3 \approx d_i/v$.

Having defined all three tasks, the time constraint facing vehicles in subregion i can be rewritten:

$$\frac{D_i}{v} + \delta d_i \tau + \frac{d_i}{v} \leq T \tag{4}$$

In designing the subregions, the underlying goal is to minimize the number of vehicles required, which is equivalent to maximizing the number of points per subregion. The design process is begun by considering the outermost delivery zone, subregion 1. Its optimal length, d_1^*, is determined by replacing the line-haul distance, D_i, in the first term of the time constraint with the line-haul distance to the first zone, $D_c - d_1$, and solving for d_1:

$$d_1^* = \frac{Tv - D_c}{\delta \tau v} \tag{5}$$

It should be noted that d_1, and all remaining calculations of d_i, can be solved in this manner only by assuming that time is the binding constraint. By substituting $[D_c - (d_2 + d_1)]$ for D_i and d_2 for d_i in the time constraint, d_2^* is easily determined. Solving recursively, an expression emerges that allows us to design zone i (for $i = 2, \ldots, n - 1$) where n is the total numbers of zones required to cover the entire city:

$$d_i^* = \frac{Tv - D_c + \sum_{j=2}^{i} d_{j-1}^*}{\delta \tau v} \tag{6}$$

The zone adjacent to the terminal, zone n, is simply the remaining length of the city,

$$d_n^* = D_c - \sum_{j=2}^{n} d_{j-1}^*$$

It will be less than the length determined by the above design equation.

Thus, given a linear city of length D_c and customer density δ, we can optimally design all subregions. We simply begin with the above expression for d_1^*, which gives the optimal size and location of the outermost subregion. Then, knowing the length d_1^*, we can determine the length of all other zones ($i = 2, \ldots, n - 1$) recursively with the above expression for d_i^*.

L_1 Metrics

A linear city is clearly an unrealistic representation of any city that would be included in air freight networks. However, the design process that applies to the hypothetical linear cities also applies to two dimensional cities. Since U.S. cities rely primarily on rectangular (L_1) transportation metrics, we need to adapt the design process to apply to such metrics. In the following pages, we apply the design approach to cities with L_1 metrics when the terminal is located in the city center, on the edge of the city, and in one corner of the city.

Terminal in City Center

First, consider a delivery area with a centrally located terminal, as shown in Figure 2(*left*). For analysis purposes, the delivery area shape is approximated as a square oriented at 45° to a fine orthogonal transportation grid (L_1 metric), a shape dictated by the equi-travel time contours (the locus of all points that can be reached in a given amount of time). The size of the delivery area is defined by D_c, which is the travel distance to the outermost corner or edge of the city. All points to be visited are distributed randomly through-

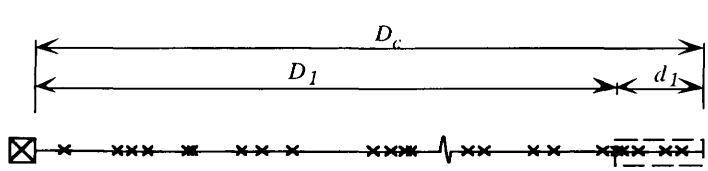

FIGURE 1 Subregion design for a linear city with one terminal on edge of city.

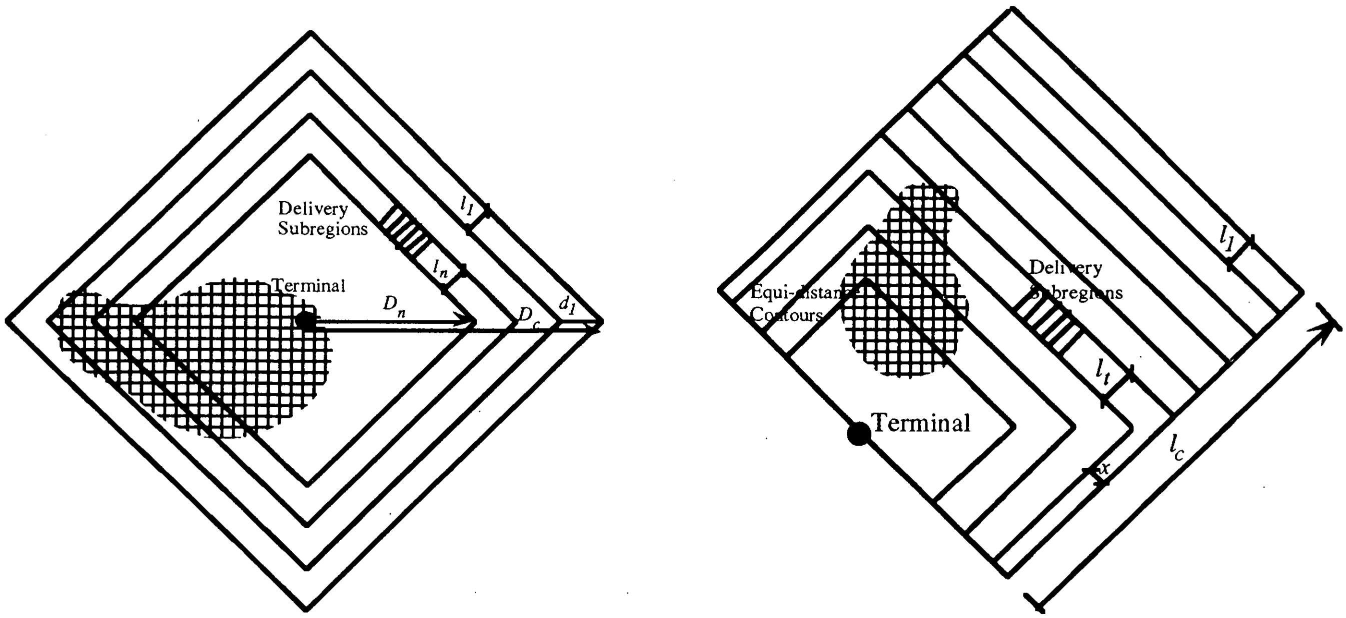

FIGURE 2 Subregion design for city with an L_1 metric and centrally located terminal.

out the area with a constant density, $\delta(x, y) = \delta$. Vehicles travel at speed v throughout the city.

The first step in designing delivery subregions is to build equi-travel time contours from the depot. For this scenario, the contours are squares centered at the depot at 45° to the metric's preferred directions. Daganzo (*12*) indicates that delivery subregions should be rectangular in shape and should be oriented perpendicular to these contours, as shown in Figure 2(*left*).

As before, the outermost delivery subregions are designed first, followed by the subregions in bands progressively closer to the terminal. Vehicles are again bound by a time constraint that includes the line-haul time, $T1$, the local travel time, $T2$, and the handling time, $T3$. Letting D_i equal the distance to the inner contour of band i, the line-haul travel time can be defined:

$$T1 = \frac{D_i}{v} = \frac{D_c - \sum_{l}^{i} d_i}{v} = \frac{D_c - \sqrt{2}\sum_{l}^{i} d_i}{v} \tag{7}$$

The handling time, $T2$, is the time required to perform the delivery and/or pickup tasks at all points in the subregion. Assuming that the required handling time per stop, τ, is constant on the average, then the total handling time is the product of the total number of points in the subregion and τ. Daganzo (*12*) illustrates that, for an L_1 metric and randomly scattered points, the tour length minimizing dimensions for delivery subregions are approximately:

$$\text{Subregion width} = (6/\delta)^{1/2} \tag{8}$$

$$\text{Subregion length} = C(6\delta)^{-1/2} \tag{9}$$

where C is the number of points in the subregion. The total number of points in a subregion, then, can be estimated by solving the second equation for $C = l(6\delta)^{1/2}$. By so doing, the total handling time for a zone in band i is approximated:

$$T2 \approx \tau l_i(6\delta)^{1/2} \tag{10}$$

The local travel distance is approximated as the product of the number of points in the subregion, defined above, and the expected travel distance between two points in a subregion. Daganzo (*12*) indicates that the expected travel distance between points is $k\delta^{1/2}$, where k is a dimensionless constant; approximately 0.82 for L_1 metrics and 0.57 for Euclidean metrics. Thus, the local travel distance is approximately $lk\sqrt{6}$, and the local travel time in a subregion in band i is:

$$T3 \approx \frac{l_i k\sqrt{6}}{v} \tag{11}$$

As in the previous section, the design process begins with the outermost band of the city, which faces the following time constraint:

$$T1 + T2 + T3 \leq T \tag{12}$$

$$\left(\frac{D_c - \sqrt{2}l_1}{v}\right) + l_1\tau(6\delta)^{1/2} + \frac{l_1 k\sqrt{6}}{v} \leq T \tag{13}$$

Solving the constraint gives the optimal length of the subregions in band number 1:

$$l_1^* = \frac{Tv - D_c}{(6\delta)^{1/2}\,\tau v + k\sqrt{6} - \sqrt{2}} \tag{14}$$

For design purposes, and particularly for cost estimating purposes, we also need to know how many delivery subregions are in each band. Having determined l_1^*, we can calculate the average perimeter of the band and the total number of subregions in band n:

$$N_i = \frac{\text{average perimeter of band i}}{\text{optimal zone width}} \tag{15}$$

$$N_1 \approx \left[\frac{4\sqrt{2}D_c - 4l_1^*}{\left(\frac{6}{\delta}\right)^{1/2}}\right]^+ \tag{16}$$

where $[]^+$ is the nearest integer greater than the quantity in brackets.

The second band, or any subsequent band, is designed in a similar process, substituting $D_c - \sqrt{2}\sum l_i$ for D_1 in the line-haul expression. Repeating this process, the following recursive design equations emerge:

$$l_i^* = \frac{Tv - D_c + \sqrt{2}\sum_{j=2}^{i} l_{j-1}^*}{(6\delta)^{1/2}\,\tau v + k\sqrt{6} - \sqrt{2}} \tag{17}$$

$$N_i \approx \left[\frac{4\sqrt{2}D_c - 8\sum_{j=2}^{i} l_{j-1}^* - 4l_i^*}{\left(\frac{6}{\delta}\right)^{1/2}}\right]^+ \tag{18}$$

The above equations can be used iteratively to design each delivery subregion in the delivery area. Note, however, that this design process will result in irregular delivery bands (and zones) adjacent to the terminal. It may be necessary to "manually" adjust subregions boundaries to cover the area in consideration, either by expanding/contracting nearby subregions or adding another subregion. Whatever method is employed, the number of additional delivery zones required is small relative to the total number of zones required for the entire delivery region.

Other Terminal Locations

Air express terminals are typically located at local airports which, more often than not, are located on the perimeters of cities due to land and noise constraints. As a result, it is not always appropriate to assume that the terminal is in the city center. Two other terminal locations have been evaluated using the procedure just described; one with the terminal located in the corner of the city, and another with the terminal in the middle of the city edge. Letting D_c equal the travel distance from the terminal to the furthest edge of the city, the Euclidean length of the city edges are $l_c = D_c/\sqrt{2}$.

When the terminal is located in the center of the city's edge, the equi-travel time contours take on a peculiar shape. The outermost bands are simply formed by straight contours. But, halfway through the city, the contours take on a rectangular shape, as shown in Figure 2(b). As a result, additional notation is required; delivery subregions on the outermost contours are in bands 1 to $(t - 1)$, the transition band is band t, and the half diamond shaped contours form bands $(t + 1)$ to n. To determine the number of subregions in the transition band, t, the zone is divided into two parts; the "crosspiece" (which is equivalent to bands 1 through $t - 1$) and the "legs" which form the edge of the city. The number of subregions in the cross-piece is given by Equation 20, and the number of subregions in the legs is estimated as the dividend of the area of the two legs and the optimal area of a subregion located in band t. Then, the design equations can be expressed:

$$N_i \approx \left[\frac{D_c}{\left(\frac{12}{\delta}\right)^{1/2}}\right]^+ \quad \text{for } i=(1, 2, \ldots, t-1), \tag{19}$$

$$N_i \approx \left[\frac{D_c}{\left(\frac{12}{\delta}\right)^{1/2}} + \frac{x}{\left(\frac{12}{\delta}\right)^{1/2}}\, l_i^*(D_c + \sqrt{2}D_c - 2\sqrt{2}l_i^* - 4\sum_{j=2}^{i} l_{j-1}^*)\right]^+ \quad \text{for } i = t, \tag{20}$$

$$N_i \approx \left[\frac{\sqrt{2}D_c - 4x - 4\sum_{j=t+1}^{i-1} l_j^* - 2l_i^*}{\left(\frac{6}{\delta}\right)^{1/2}}\right]^+ \quad \text{for } i=(t+1, \ldots n-1), \tag{21}$$

$$N_i \approx \left[\frac{4l_i^*}{\left(\frac{6}{\delta}\right)^{1/2}}\right]^+ \quad \text{for } i = \text{n}, \tag{22}$$

where

$$x = \sum_{i=1}^{t} l_i^* + \frac{D_c}{2\sqrt{2}}$$

is the distance between contour t and the edge of the city.

The third scenario (terminal in the city corner) has associated with it a set of design equations similar in nature to the city center scenario originally considered:

$$N_1 \approx \left[\frac{\sqrt{2}D_c - l_i^*}{\left(\frac{6}{\delta}\right)^{1/2}}\right]^+ \tag{23}$$

$$N_i \approx \left[\frac{\sqrt{2}D_c - 2\sum_{j=2}^{i} l_{j-1}^* - l_i^*}{\left(\frac{6}{\delta}\right)^{1/2}}\right]^+ \quad \text{for } i = (2, \ldots, n-1) \tag{24}$$

$$N_n \approx \left[\frac{l_n^*}{\left(\frac{6}{\delta}\right)^{1/2}}\right]^+ \tag{25}$$

FAST ROADS

The models presented in the previous sections assume that vehicles travel the same speed on all roads. Since city networks are combinations of local roads, arterials, and freeways, the aforementioned models must be expanded to allow for more than one travel speed.

Newell (*13*) examines the impact that fast roads have on the shape of equi-travel time contours, demonstrating that a single fast road stretches the contours in the direction of the road. Kiesling (*14*) indicates that a grid of fast roads, which arguably exists in any major city, results in equi-travel time contours that are closely approximated by a contour oriented at 45° to the origin as in the previously analyzed case in which no fast roads are present.

The approximated equi-travel time contour is dependent on previously defined variables and two vehicle travel speeds, v_f (fast) and v_s (slow). If we assume that delivery vehicles travel fast on the line-haul portion of their delivery tour, and travel slow on local portions of the tour, the original time constraint can be rewritten:

$$\frac{(D_c - \sqrt{2}l_1)}{v_f} + l_1\tau(6\delta)^{1/2} + \frac{l_1 k\sqrt{6}}{v_s} \le T \tag{26}$$

Solving the constraint as in Section 2, we can determine the optimal zone lengths:

$$l_1^* = \frac{Tv_f - D_c}{(6\delta)^{1/2}\tau v_f + \frac{k\sqrt{6}v_f}{v_s} - \sqrt{2}} \tag{27}$$

$$l_i^* = \frac{Tv_f - D_c + \sqrt{2}\sum_{j=2}^{i} l_{j-1}^*}{(6\delta)^{1/2}\,\tau v_f + \frac{k\sqrt{6}v_f}{v_s} - \sqrt{2}} \quad (28)$$

The above expressions are true no matter where the terminal is located. However, the definition of D_c changes for each scenario. Generally speaking, D_c is the travel distance from the terminal to the furthermost point on the city boundary.

The optimal zone length is now a function of two speeds. But, what about the number of subregions in each band? None of the previously defined expressions change simply because, in all previously analyzed scenarios, the number of subregions in each band is not a function of v. Thus, the design of all delivery subregions in metrics with fast roads is identical to the previously described process with the exception that the optimal zone length changes.

LOGISTIC COSTS OF GROUND-SIDE DELIVERY

The heuristic developed and demonstrated up to this point provides all of the information needed to locate and size delivery subregions which, in turn, allows us to begin analyzing ground-side pickup and delivery costs. In this section, a basic cost model is developed that incorporates four categories of logistics cost; costs of stopping, costs of overcoming distance, costs of carrying additional freight, and fixed vehicle costs.

Included in the time constraint that underpinned the development of our design algorithm is the time required to stop at an origin or destination and move the package to/from the delivery vehicle. Several costs are incurred each time the delivery vehicle stops including labor, vehicle depreciation costs and materials. The total cost of stopping is determined by assuming that the cost per stop, C_s, is constant on the average. Including the entire ground-side delivery system, the total number of stops is the sum of city-wide stops and stops at the local terminal. Thus, the total stopping cost follows:

$$\text{Stopping cost} = C_s\left(A\delta + \sum_{i=1}^{n} N_i\right) \quad (29)$$

where A is the area of the region in question.

The cost per mile, C_d, is also assumed constant on the average. Recalling the need to include both line-haul trips in the cost formulation, the total distance traveled is easily determined:

$$\text{Total distance} = 2\sum_{i=1}^{n} D_i^* N_i + k\sqrt{6}\sum_{i=1}^{n} l_i^* N_i \quad (30)$$

$$\text{Distance cost} = C_d\left(2\sum_{i=1}^{n} D_i^* N_i + k\sqrt{6}\sum_{i=1}^{n} l_i^* N_i\right) \quad (31)$$

where $D_i^* = D_c - \sum_{j=1}^{i} l_j$ and $D_n^* = 0$.

We also include the added cost per item carried, C_m, in the formulation. The total number of items carried is the product of the number of stops and the number of packages per stop, z:

$$\text{Marginal cost} = C_m(A\delta z) \quad (32)$$

The marginal costs are very small compared to other logistics costs and are frequently ignored.

The final cost to include in this model is the fixed vehicle cost, C_v^f. The total number of vehicles required to deliver freight throughout the city is assumed equivalent to the number of delivery subregions in the city:

$$\text{Fixed vehicle cost} = C_v^f\left(\sum_{i=l}^{n} N_n\right)$$

The total cost of delivery, TC, can then be expressed as the sum of the aforementioned costs:

$$TC = C_s\left(A\delta + \sum_{i=1}^{n} N_i\right) + C_d\left(2\sum_{i=1}^{n} D_i^* N_i + k\sqrt{6}\sum_{i=1}^{n} l_i^* N_i\right) + C_m(A\delta z) + C_v^f\left(\sum_{i=1}^{n} N_i\right) \quad (34)$$

To demonstrate the economic characteristics of this model, we consider a diamond-shaped city with an L_1 metric and a terminal located in the lower corner. In such a case the city area, A, is l_c^2, or $D_c^2/2$. Table 1 summarizes the parameter values assumed for the remainder of this section.

The results of the subregion design algorithm confirm *a priori* expectations about the subregion partitioning, that bands furthest from the terminal are narrowest ($l_1 \approx 1.74$ km), and bands closest to the terminal are widest ($l_7 \approx 6.13$ km) with the exception of band n. It is easily shown that bands i to $n + i$ increases by the constant percentage

$$\left((6\delta)^{1/2}\tau v_f + \frac{2v_f}{v_s} - \sqrt{2}\right)^{-1}$$

To assess the concepts of scale and density economies in ground-side delivery operations, the total cost formulation is used to determine average costs (total cost per package) of delivery under various assumptions. Scale economies are defined as a change in the average unit costs of production resulting from a change in output. If output is defined as the number of points visited by a carrier, which increases as a result of city growth (D_c increasing, *ceteris paribus*) or an expansion in the carriers delivery market, it is easily shown that there are diseconomies of scale. If δ increases while holding D_c and all other variables constant (which is more accurately called economies of density), it is clear that there are profound economies of density in ground side freight distribution, as indicated by the decreasing average unit cost curve in Figure 3. Although the finding of such significant economies of density is not

TABLE 1 Assumed Parameter Values for Demonstration of Cost Model

Parameter	Assumed Values
δ	0.39 to 9.67 stops/km² (1 to 25 stops/mi²)
D_c	40.2 km (25 mi)
T	1 to 4.5 hr
v_f	64.4 kph (40 mph)
v_s	32.2 kph (20 mph)
t	5 min
k	0.82
z	1 to 4.5 pkg/stop
C_d	$0.62/km ($1/mi)
C_s	$2/stop
C_m	$0.05/pkg
C_v^f	$1.25/veh

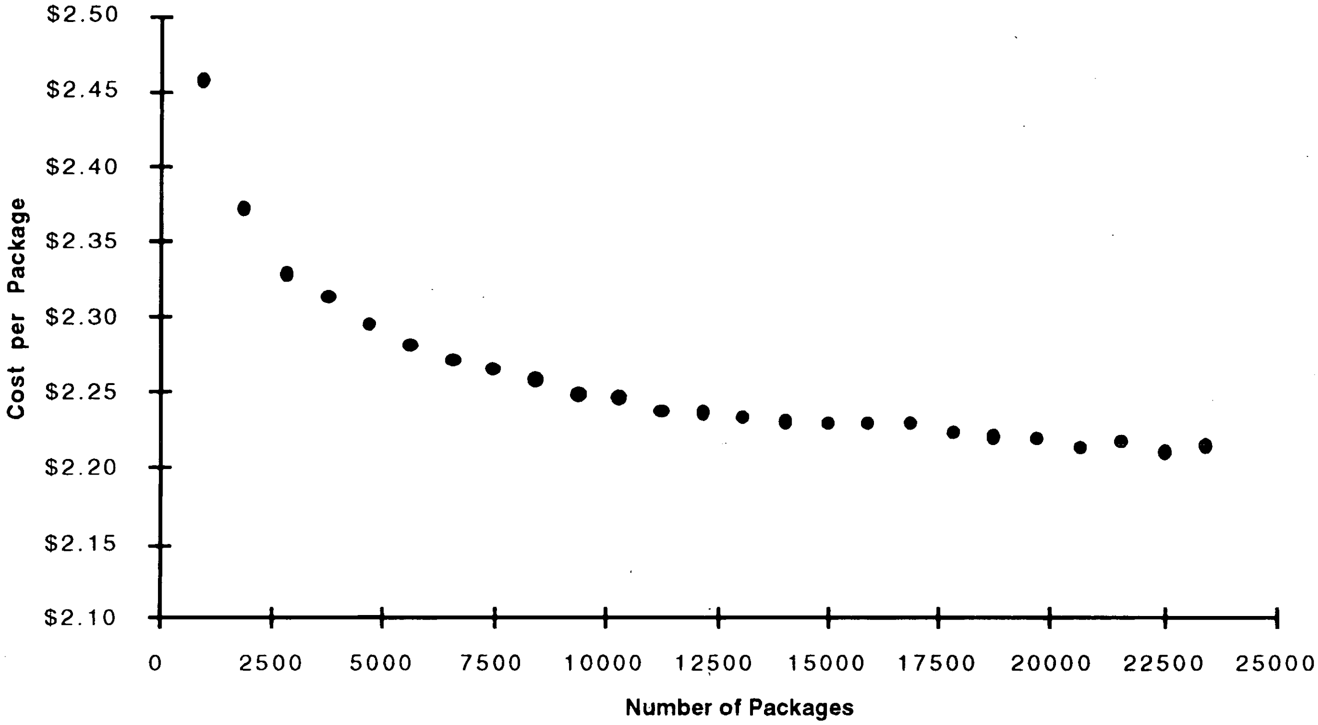

FIGURE 3 Economies of density in ground-side pickup and delivery operations.

surprising, this result has particular importance in the analysis of carrier competition when coupled with the impact that the time constraint has on operational costs, discussed below.

As discussed in the introductory section, *time* may be the most important strategic decision variable facing air freight carriers. There are two competing effects of varying the time constraint, T. First, increasing T lowers average unit costs significantly, *ceteris paribus*. The reason is simply that if T increases, the number of required delivery subregions decreases, thus lowering the operational costs. In a competitive setting, it may appear that a combination carrier would therefore want to make the time constraint as large as possible to minimize costs. There are several potential trade-offs to increasing T, however. To illustrate, consider the ways in which an increase in T can be accomplished. First, it can be accomplished by setting the pickup deadline earlier (or the delivery deadline later). However, this would diminish the level of service offered to the customer, causing some customers to select another carrier or not purchase the product at all. Second, it could also be accomplished by serving a smaller market (within a city). In other words, reduce the area served from a terminal. Third, it could be accomplished by reducing the number of destination cities served from an airport. A combination carrier, for example, may have departing flights to Phoenix and Chicago at 6:30 p.m. and 7:00 p.m., respectively. With a 4:30 package pickup deadline, both destinations are served by a 1.5-hr time constraint (allowing 0.5 hr to load aircraft). T could be increased to two hours if only Chicago bound packages are served. Thus, T can be increased in several ways, including combinations of the above methods. The trade-off, however, is that any of the aforementioned "solutions" *reduces* the demand served by the carrier, which *increases* average units costs according to the previously illustrated economies of density.

The trade-off between economies of density and "economies of time" can be illustrated two ways. First, we can assess the impact of varying T on average unit costs, taking into account the decrease in available demand caused by an increase in T. Clearly, at $T = 0$, the maximum number of points are potentially served (although there is no way to service the pickup and delivery points in zero time). Furthermore, it is appropriate to assume that the entire market (δA) is available for time constraints up to 2 hr. For T greater than approximately 2 hr, however, the number of points that can be serviced begins to decline for the previously discussed reasons. Eventually, no demand is available at $T \approx 9$ hr, the full business day. The available demand (AD) distribution could be represented as follows:

$$AD = \delta\left(1 - \left(\frac{e^{T-y}}{1 + e^{T-y}}\right)^{x}\right) \tag{35}$$

where x and y are distribution shape parameters, assumed to be 2 and 4 for demonstration purposes. The available demand (as a function T) is illustrated in Figure 4. Substituting this "available demand" quantity into the total cost model (Equation 34) and varying T from 0 to 9, Figure 5 illustrates that the cost minimizing time constraint is from 5 to 7 hr, but the improvement in costs over $T \approx 3$ is relatively small. Profit maximization is more important than cost minimization for a freight carrier, however, so a more appropriate way to view the effect of time on production strategy is to consider the impact that the time constraint has on carrier profits. Assuming an average price per package of \$10, Figure 6 illustrates that the profits of a hypothetical carrier are maximized when the time constraint is approximately 1.5 hr (for this example).

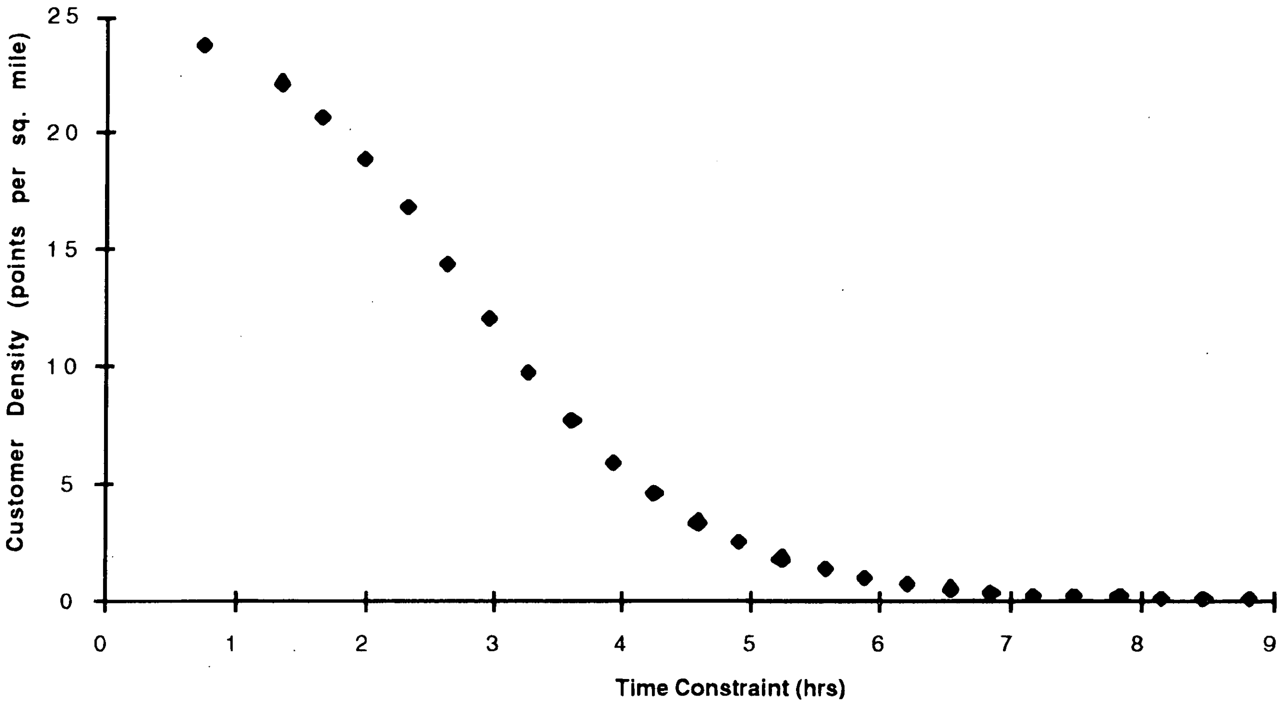

FIGURE 4 **Available customer density as a function of time constraint, *T*.**

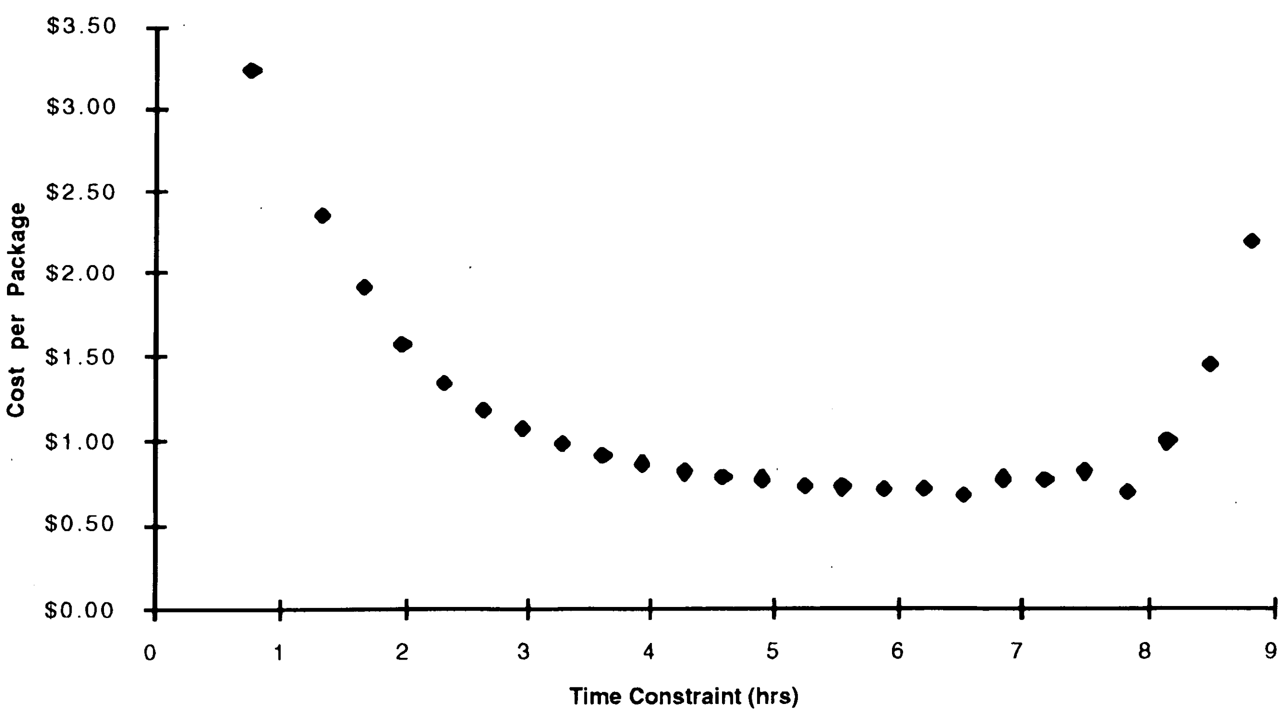

FIGURE 5 **Average unit costs as a function of time constraint, *T*.**

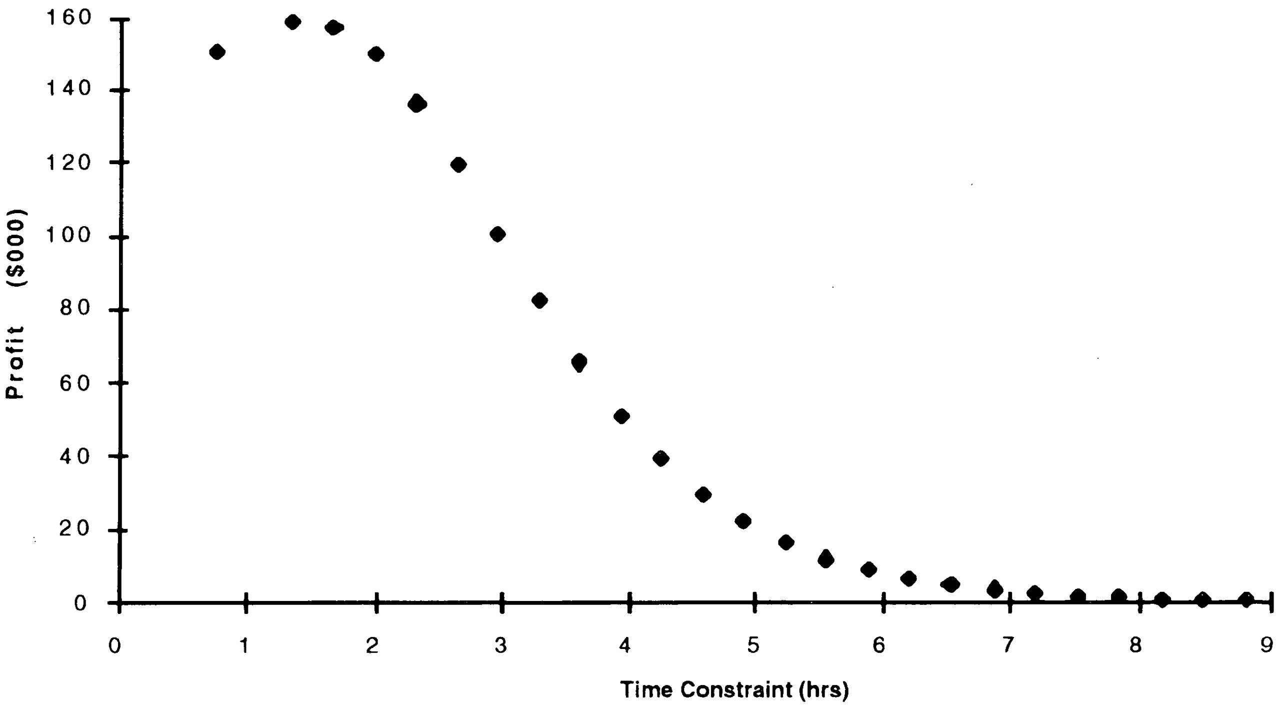

FIGURE 6 Carrier profit as a function of time constraint, *T*.

CONCLUSIONS

Throughout this report, several aspects of the design of ground-side delivery systems have been explored. It was first indicated that the binding design constraint is that of time, not vehicle capacity constraints as assumed by most previous studies. It was further indicated that an appropriate way to approach the design of delivery subregions is to first define the time constraint as a function of line-haul time, handling time, and local travel time. Then, according to this time constraint, design the delivery subregions along the equi-travel time contours beginning in the outermost band and iteratively moving toward the terminal. Expressions were derived for the subregion dimensions, the number of subregions per band, and the location of the subregions for cities employing L_1 metrics with terminals located centrally, in one corner of the city, and in the middle of one edge of the city.

City street networks generally allow for more than one speed of travel. Fast roads, as they are often called, significantly change the shape of the equi-travel time contours that the design is based on. As a result, the impact of fast roads in a city network was explored. The design framework was then generalized to allow for two travel speeds; fast travel on line-haul trips and slower travel on local streets.

The results of the design process for a square city with an L_1 metric, two travel speeds, and a terminal in one corner, were then used to develop a total cost model of ground-side pickup and delivery operations. The model, in turn, was used to explore the economic cost structure of the delivery system. It was indicated that ground-side pickup and delivery operations exhibit significant economies of scale and profound economies of density. The results were highly robust with respect to changes in all design variables. It was also demonstrated that as the time constraint increases, the average unit cost decreases. However, increasing this decision variable results in a decrease in the market that is potentially captured by a competing carrier.

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Challenges in Developing an Airport Employee Commute Program: Case Study of Boston Logan International Airport

DIANE M. RICARD

Boston Logan International Airport, a major trip generator, contributes to and is impacted upon by traffic congestion in the Greater Boston area. Located about 3 km from downtown Boston, Logan is the fifth largest airport in the United States in terms of origin-destination air passengers. Logan origin-destination passengers begin or end their air travel in the Boston region and affect the Boston regional transportation system. Because air passenger growth must be accommodated within the existing airport boundaries and regional roadways, restrictions imposed by the Logan Airport Parking Freeze, and by a responsibility to help reduce regional environmental impacts, it has become increasingly important to find feasible ways to reduce the vehicle trip generation rates of the various Logan Airport user groups. The commuting patterns of the 16,000 Logan employees, who account for about 20 percent of average annual weekday traffic, are characterized in this paper. Data presented in the paper are based on the results of an airport employee survey conducted in 1990. Commute profiles of both flight crews (who exhibit travel characteristics similar to those of air passengers) and non–flight crew employees are highlighted. Since the airport is staffed 24 hours a day with various types of workers, feasible solutions to reduce airport employee trips will be different from measures tailored to influence commute habits of the traditional office workers. In this paper available alternatives to the single-occupant private automobile are discussed, and their effectiveness relative to employee demand is assessed. There is a small employee market for most alternatives currently available, as each service was developed primarily for air passengers or downtown commuters. Finally, a summary is presented of the initiatives that the Massachusetts Port Authority (owner and operator of Logan International Airport) has taken in the past and is considering in the future to encourage employees to use higher-occupancy commute modes.

Boston Logan International Airport, owned and operated by the Massachusetts Port Authority (Massport) is a major trip generator. Logan contributes to and is affected by traffic congestion in the greater Boston area. Located about 3 km from downtown Boston, Logan is the fifth largest airport in the United States in terms of origin-destination air passengers. Logan origin-destination passengers begin or end their air travel in the Boston region, and affect the Boston regional transportation system.

Reducing air passenger and employee vehicle trips is important to Massport from an air quality perspective and from an airport management perspective. On an average weekday in 1992, about 85,000 vehicle trips were generated by Logan Airport. By comparison, Boston proper generated about 756,000 vehicle trips on an average weekday in 1992 (source: Central Transportation Planning Staff, 1992 Interim Regional Model Set). About 60 percent of vehicle trips to and from Logan are made by air passengers, and another 25 percent are made by Logan employees. For a number of years, Massport has been successfully promoting, maintaining, and improving an aggressive air passenger ground-access program aimed at reducing the number of vehicle trips per air passenger trip. The nature of the Logan working environment has made it much more difficult to provide a comparable access program for employees.

Assistant Director of Economic Analysis, Massachusetts Port Authority, 10 Park Plaza, Boston, Mass. 02116-3971.

Within the existing menu of transportation services available to air passengers and downtown commuters, Massport offers some incentives to employees who are seeking alternatives to the drive-alone commute. However, many Logan employees cannot commute using these services, because they were developed for customers with different travel requirements.

In this paper the challenges Massport faces in developing a successful, cost-effective employee access program are presented through a description of the access characteristics of Logan and the Logan work environment. The commuting patterns of Logan employees are characterized, available commute options are described, and initiatives that Massport currently offers or is considering in the future to encourage commuting in higher-occupancy modes are discussed.

ACCESS CHARACTERISTICS OF LOGAN AIRPORT (*1*)

A number of characteristics of the Boston regional transportation system, the placement and size of the airport, and the airport's proximity to neighborhoods all make access to Logan difficult during certain times of the day and week, and present significant operations management challenges for Massport. The characteristics may be categorized as follows:

1. The greater Boston area and the New England region are principal destinations for both business and pleasure travelers, and are located on one of the most heavily-traveled air corridors in the U.S. (Boston, New York, and Washington, D.C.). Ninety percent of these passengers are using the Boston local transportation infrastructure to access Logan (rather than flying into and out of Logan on their way to another destination).
2. The airport is served by a limited number of access routes (two cross-harbor tunnels and one bridge), which do not have the capacity to handle easily the volume of traffic using the system during periods of high demand.
3. Because of Logan's proximity to downtown Boston, the regional highway and public transportation system is focused on Boston in a series of radial routes converging on the central business district. Airport traffic mixes with regional vehicular traffic,

and use of the subway, commuter rail, and bus system requires transfers in downtown Boston to reach the airport. The length of time required to reach the airport and the inconvenience of the transfers makes public transportation a difficult choice for frequent airport users, such as employees.

4. Due to the restricted availability of land for airport development and Massport's commitments to the neighborhoods around the airport, the size of Logan Airport is fixed at its present area. Massport is committed to accommodating airport growth within the existing airport boundaries.

5. Responding to environmental and community responsibilities, Massport has committed to a moratorium on the number of airport parking spaces and to limiting traffic accessing the airport by way of local neighborhood streets. As part of this moratorium, Massport has committed to relocating about 30 percent of on-airport employee parking spaces to off-airport locations.

THE LOGAN WORK ENVIRONMENT

The Logan work environment presents a challenge for developing a responsive and cost-effective employee commute program. Standard transportation demand management options, such as flextime, vanpooling, or carpooling on a regular basis, are an option for only a small proportion of the population due to nontraditional work schedules.

Logan Airport operates 365 days a year, 24 hours a day. Holidays and popular vacation periods, when many businesses slow down, are some of the busiest times at an airport. Because the almost 16,000 people are employed at Logan to maintain its continuous operation, the concentration of employees commuting during standard business hours is sparser than in other industries. On an average weekday, only 60 percent of all employees commute to Logan, and only 25 percent of all employees arrive between 6:00 a.m. and 10:00 a.m. Between 30 percent and 40 percent of employees staff the airport on Saturdays and Sundays.

There are 140 employers at Logan. Seven major airlines are responsible for about 55 percent of employees, and Massport employs about 4 percent. Many employee work schedules are related to air passenger demand and flight operations. These employees may be subject to either scheduled or nonscheduled overtime, and do not have flexibility in their work schedule. Nonscheduled overtime is tied to flight delays and cancellations, events that are very difficult to predict and plan for. The numerous airport-wide shifts, which vary by company, make it difficult to develop commute options around particular shifts.

Many Logan employees have benefits packages that are based on contractual agreements or national company policies. Groups of workers at Logan belong to various unions. A collective bargaining agreement may limit the incentives to high-occupancy commuting or disincentives to the drive-alone commute that can be offered to a group of employees. Similarly, airline-wide employee policies may limit what a local airline station manager may provide employees as alternative commute incentives, especially now, when airlines are trying to cut costs to remain competitive.

LOGAN EMPLOYEES

The following is a brief profile of Logan Airport employees, presented to show the uniqueness and complexity of an employee population at a major airport. Most of the information is based on an employee commute survey administered in the spring of 1990, which was answered by 15 percent of employees. Since the Logan work environment and available commute options have not changed much since 1990, Massport believes that the survey continues to explain overall commuting behavior. A copy of the survey instrument is included as Figure 1a. Table 1 is a summary of pertinent commute characteristics of Logan Airport employees.

A separate survey form was administered to Boston-based flight crews. All of the survey questions were the same as in the non–flight crew survey, with the exception of the following replacements (Figure 1b). Question 22 on the non–flight crew survey was not asked of flight crews.

Commute Modes

Currently there are time and cost incentives for most Logan employees to commute by automobile compared to alternative modes. As at most U.S. airports, the majority of Logan employees enjoy parking privileges on or near the airport, fully subsidized by their respective employers. All of the major airlines subsidize employee parking at airports throughout the United States. It would be difficult for an airline to discontinue this benefit at some airports and provide it at others. In terms of competitive hiring, it would also be difficult for an airline to discontinue the employee parking subsidy unless other airlines were doing the same thing.

Almost all of the surveyed employees reported that their employer does not subsidize public transportation. On an average weekday about 90 percent of Logan employees commute to Logan by automobile, and most of them are commuting alone. Another 10 percent of employees commute by subway, and the remainder walk, take a bus, or use other means to get to Logan. By comparison, the transit share of employees commuting to Boston proper is 44 percent (source: Central Transportation Planning staff, based on the 1990 Census).

Of employees commuting by subway, less than half have access to employer-subsidized parking. Twice the proportion of automobile commuters have access to employer-subsidized parking as do subway commuters. Subway commuters have fewer automobiles per adult available in the household compared to automobile commuters. The data indicate that the majority of employees commuting by subway are doing so because an automobile or airport parking is not available to them.

From most towns, depending on the time of day, the commute time by automobile offers the employee a noticeable time savings over scheduled high-occupancy vehicle services. This will be discussed further under the section Employee Alternatives to the Automobile.

Geographic Concentrations

The 10 towns with the largest concentrations of Logan employees are all in the immediate vicinity of the airport. For the 40 percent of Logan employees residing in these towns, Logan is a quick trip by automobile. For many, the extra time involved in carpooling or using public transportation is viewed as an unnecessary inconvenience.

Job Categories

Twenty-five percent of Logan employees are traditional office workers, 25 percent hold sales or service related positions, and 25

Logan Airport Employee Survey

Why you have been given or sent this questionnaire

This survey is being carried out to give Massport an up-to-date picture of the travel needs of people who work at the airport. To plan for the Third Harbor Tunnel and other developments, we need to find out how airport employees are currently getting to and from work. Please take a minute or two to answer these questions.

If you received this questionnaire at home...

please fill it out today, fold it so that the return address shows on the outside, then put it in the mail.

If you received this questionnaire at work...

please fill it out today and drop it in one of the marked boxes at your workplace; or fold it so that the return address shows on the outside and put it in the mail. Don't return a questionnaire at your workplace if you've already returned one that you got in the mail.

Thank you for your help; it is important to us. All replies are confidential.

Sincerely,

Patrick B. Moscaritolo
Director, Logan Airport

About your journey to work:

1. **Today's date is...** *(Check one day and fill in date)*

1 ☐ Monday
2 ☐ Tuesday
3 ☐ Wednesday
4 ☐ Thursday
5 ☐ Friday
6 ☐ Saturday
7 ☐ Sunday

_____/_____/90
month date

2. **Think back over the last seven days. On which of those days did you go to work at Logan?** *(Check every day on which you traveled to work at the airport)*

1 ☐ Monday
2 ☐ Tuesday
3 ☐ Wednesday
4 ☐ Thursday
5 ☐ Friday
6 ☐ Saturday
7 ☐ Sunday

Think about the *most recent* time when you went to work at Logan and then returned home again. You should answer questions 3 through 14 about your trips to and from work on that occasion.

3. **The day on which you arrived at Logan on that occasion was...** *(check one day only)*

1 ☐ Monday
2 ☐ Tuesday
3 ☐ Wednesday
4 ☐ Thursday
5 ☐ Friday
6 ☐ Saturday
7 ☐ Sunday

4. **On that day, from where did you start your trip to go to work at the airport?**
Please specify:

__________ town or city __________ state __________ zip code

__________ street address or nearest intersection

office use only: ☐

5. **Is this place...** *(check one only)*

1 ☐ your own home?
2 ☐ some other place?

6. **At what time did you get to the airport on that day?**

Enter time: ☐ hr. : ☐ min. 1 ☐ A.M. 2 ☐ P.M.

7. **How did you arrive at the airport on that day?**
(Check one only)

1 ☐ *driving* a private vehicle (car, van, or light truck)
2 ☐ *passenger* in a private vehicle
3 ☐ MBTA Airport station and Massport shuttle bus
4 ☐ MBTA Airport station and employer pickup
5 ☐ MBTA Airport station and walk
6 ☐ MBTA Wood Island station
7 ☐ MBTA, any other station
8 ☐ airport shuttle bus, without taking the MBTA
9 ☐ Logan Express bus
10 ☐ other bus
11 ☐ other means (specify)

If you checked an answer in this box (that is, you did not travel by private vehicle), skip to question 13

FIGURE 1a Logan Airport employee survey.

8. **If you went to work by private vehicle on the day in question, how many people were in the vehicle in total, including yourself?**
Enter number: [|]

9. **Was the private vehicle parked...** *(check one only)*
 1☐ in your employer's parking area immediately beside your place of work?
 2☐ in Massport's Bird Island Flats employee lot?
 3☐ in a passenger parking garage or lot (Terminal A, B,D, or E, or Central Parking)?
 4☐ *near* the airport, off airport property?
 5☐ or was it *driven away* from the airport, and not parked nearby?
 6☐ other *(specify)* ______

10. **If the private vehicle was parked at or near the airport, what was the cost *to you* for parking?** If some of the costs are paid by your employer or by other passengers, count only *your own share* of the costs.
 1☐ parking didn't cost me anything
 2☐ parking cost me $ [| |] . [|] (dollars . cents) 1☐ per day 2☐ per month

11. **On your private vehicle trip to work, did you make any stops to pick up or drop off other people, or to do errands?**
 1☐ yes, I made stops on the way
 2☐ no, I came straight to the airport

12. **On your private vehicle trip to work, did you travel...** *(check all that apply)*
 1☐ through the Callahan Tunnel?
 2☐ on the Central Artery, from the south ("South Station tunnel")?
 3☐ on the Central Artery, from the north?
 4☐ on Route 1, from the north?
 5☐ by none of these routes?

13. **On the day in question, did you leave the airport again *before* you finished work?**
(Check all answers that apply to you)
 1☐ no, I stayed at the airport until I finished work
 2☐ yes, my job requires me to spend most of my working time away from the airport
 3☐ yes, I left by private vehicle (car, van, or truck)
 4☐ yes, I left by other means (MBTA, ferry, taxi, walk, etc.)

If you *did* leave the airport during your working period, how many times did you leave the airport for...
... *job-related* purposes? [|]
... *personal* reasons? [|]

14. **After work on that occasion, at what time did you leave the airport?**
Enter time: [|] (hr.) : [|] (min.) 1☐ A.M. 2☐ P.M.

15. **You've now told us how you traveled to and from your work at the airport on one particular occasion. How do you *usually* get to and from work? Is that in the same way as on the occasion you've told us about?** *(Check one only)*
 1☐ yes, I usually go to work in the way I've already described
 2☐ no, I usually go by car or van that is parked at the airport
 3☐ no, I'm usually dropped off (and picked up) at the airport by a car or van
 4☐ no, I usually go by public transportation (or walk)
 5☐ other *(specify)* ______

16. **If for some reason the transportation you usually use to get to the airport wasn't possible for a long period of time, how would you get to work?** *(Check one only)*
 1☐ by private vehicle (car, van, light truck) parked at the airport
 2☐ dropped off (or picked up) by private vehicle (car, van, light truck)
 3☐ MBTA Blue Line
 4☐ Logan Express bus
 5☐ other bus service
 6☐ other means *(specify)* ______

About your job at the airport:

17. **Which of the following statements best applies to you?** *(Check one only)*
 1☐ I have only one job at the airport
 2☐ I have two or more different jobs at the airport
 → How many different jobs do you currently have?
 Enter number: [ ]

18. **For which company do you work at the airport?** *(If you have more than one job, give the one you spent most time at on the occasion you described earlier)*

Enter company name: ______

office use only: [| |]

FIGURE 1b Logan Airport flight crew survey questions.

percent are flight crew members. The remainder hold a variety of positions, including maintenance and ramp service. Only about 15 percent of employees have more than 15 min of flexibility in their work schedules. This suggests that of the employees holding positions that are not firmly fixed to a schedule, most are already eligible for flextime. Flextime increases the number of carpool and high-occupancy vehicle alternatives potentially available to an individual employee.

Massport, through survey analysis, has found no significant differences in commute patterns of employees by job classification, with the exception of flight crew members compared to non–flight crew members.

19. **Where at the airport do you report to that job?**
(Check one only)

1 ☐ Terminals, old or new towers, or parking garages
2 ☐ north cargo area (Marriott kitchen, Delta hangar, NW/TWA hangar, Pan Am freight, etc.)
3 ☐ south cargo area (Bird Island Flats, Mass Tech Center, general aviation, post office, etc.)
4 ☐ rental car facilities
5 ☐ Hilton hotel, MPA heating plant, or American air freight
6 ☐ other *(specify)* ____________

20. **How much flexibility do you usually have in choosing the time you report for work?**
(Check one only)

1 ☐ none at all
2 ☐ up to 15 minutes
3 ☐ 16 to 30 minutes
4 ☐ 31 to 60 minutes
5 ☐ up to 2 hours
6 ☐ more than 2 hours

21. **Sometimes employers share some of their employees' costs of getting to and from work, or of parking at work. In the following list, please check any form of help that you personally *qualify for* (even if you don't use it).**
(Check all that apply)

1 ☐ employer provides free parking spaces
2 ☐ employer pays part (or all) of the cost of parking
3 ☐ employer pays part (or all) of the cost for public transportation
4 ☐ employer provides car (or helps with car purchase or loan)
5 ☐ employer reimburses gasoline or mileage costs
6 ☐ employer reimburses tunnel or highway tolls
7 ☐ none of the above

22. **Which one of the following categories best describes your job at Logan?** *(Check one only)*

1 ☐ executive/managerial
2 ☐ professional/technical
3 ☐ administrative support/clerical
4 ☐ sales/service
5 ☐ production/crafts
6 ☐ maintenance/trade
7 ☐ other *(specify)* ____________

About yourself:

23. **Unless you already did so at question 4, please tell us where your home is:**

____________ city or town ____________ state ____________ zip code

____________ street address or nearest intersection

office use only: ☐

24. **How many of the people living in your household *(including you)* are...**

...aged 17 or over *Enter number:* ☐

...aged 16 or less *Enter number:* ☐

...employed for 10 or more hours per week? *Enter number:* ☐

25. **How many private motor vehicles (cars, vans, or light trucks) are available for use by members of your household?**

Number of vehicles available: ☐

FIGURE 1 (continued)

Flight Crew Members

As mentioned above, about 55 percent of employees work for seven major airlines at Logan. But the group of all airline employees is not necessarily an easy target for trip reduction, since 45 percent of this group are flight crew members, and a good deal of them do not travel during peak commute periods. Flight crews, accounting for 25 percent of Logan employees, are only responsible for about 10 percent of average weekday commute trips.

Flight crews are the pilots and flight attendants who are based in Boston and commute to Logan to begin their flight assignment (called a tour of duty). A tour of duty will begin and end at Logan Airport, but often it lasts for several days. The average tour of duty for Boston-based flight crew members is 3 days, meaning the egress trip from Logan is taken 2 days after the access trip.

Due to employee flying time restrictions imposed by the Federal Aviation Administration and individual airlines, a flight crew member does not generate many commute trips per month. For instance, Federal Aviation Regulations prohibit flight crew members from flying more than 1,000 hours per year, or 100 hours per month, or from flying for more than 30 hours in any seven-day period (*2*). For most flight crew members, a private automobile is used to commute

26. **Employee parking spaces are likely to be less conveniently located during the construction of the Third Harbor Tunnel. In your opinion, how can Massport help make your commuting more convenient?**

____

____

____

____

____

office use only: ☐

Completely optional:

If you would like to enter our drawing for five free dining-out certificates, we need your name and telephone number. Otherwise, you may leave this blank.

Your name: ____________________________
please print

Telephone: (_____) __________________________
area code

This number is 1 ☐ work 2 ☐ home

Now please drop this form in any mailbox. If you received it at work, drop it in the marked box at your workplace. Thank you for your help. It is very important to us.

FIGURE 1 (continued)

to Logan, and is parked at Logan for the duration of the tour of duty. The irregularity of commute hours and days make it difficult for a flight crew member to participate in a carpool or vanpool. It is particularly difficult for a flight crew member to plan on using an alternative to the single-occupant automobile for the trip from Logan to home, since the timing depends on the arrival time of a scheduled flight, which may experience delays. Furthermore, flex-time is not a consideration for a flight crew member, as work assignments are scheduled around specific flights.

Pilots tend to live farther away from Logan compared to other Logan employees as a result of higher-than-average incomes and the need for fewer average commute trips per month. Their sparser geographic concentrations further accentuate the difficulty in developing reasonable commute options for this employee group.

Non–Flight Crew Members

Non–flight crew employees are responsible for the continuous operation of Logan Airport. On an average weekday, 90 percent of commute trips are made by this catch-all group of employees. A non–flight crew member generally has a work day that is between eight and ten hours. Individual work schedules take on a range of forms including standard business hours, fixed shifts, and varying hours by day, by quarter, or other time increments. Some

13. For your tour of duty ("trip" or "block") that began with the trip to work that you have just described, on what day of the week did (or will) you end back at Logan airport and leave work?

1 ☐ Monday
2 ☐ Tuesday
3 ☐ Wednesday
4 ☐ Thursday
5 ☐ Friday
6 ☐ Saturday
7 ☐ Sunday

14. On that day, at what time did you (or do you expect to) leave the airport after finishing work?

Enter time: [hr.] : [min.] 1 ☐ A.M. 2 ☐ P.M.

About your job at the airport:

17. **Are you...** *(Check one only)*

1 ☐ a flight attendant
2 ☐ a cockpit crew member

18. **For which airline do you work?**

Enter airline name: ______________

office use only: [ ]

20. In what year did you first start to work from a base at Logan Airport, in either your current or a previous job?

Enter year: 19 [ ]

FIGURE 1 *(continued)*

are not required to be at the airport at particular fixed hours, others have scheduled overtime, and others are subject to nonscheduled overtime.

Logan Employee Potential for Traditional Carpooling

The variety of work schedules and inflexibility of work hours limit the pool of employees that can take advantage of traditional carpools or vanpools as an alternative to the drive-alone commute. Flight crew members have an uncertainty in timing the egress trip that may be better served by an on-demand service or a regularly scheduled high-frequency service. This is also the case for non–flight crew employees subject to unscheduled overtime. The next section describes services currently available and their ability to accommodate Logan employees.

EMPLOYEE ALTERNATIVES TO THE AUTOMOBILE

A variety of high-occupancy modes serve the airport, including subway, ferry, limousine and publicly and privately operated scheduled bus service. All of the services were developed primarily for air passengers or downtown commuters.

Keeping in mind that the majority of Logan employees have access to an employer-subsidized parking space at Logan, for one or several of the following reasons the high-occupancy services

TABLE 1 Select Logan Airport Employee Commute Characteristics

	Non Flight Crew	Boston-Based Flight Crew	Total
Total Logan Airport Employees:	11,764	3,841	15,605
Average Weekday Employees	8,588	982	9,570
Proportion, Average Weekday Over Total Employees	73%	26%	61%
Work at Least One Weekend Day	51%	36%	47%
Average Length of Work Day (Time at Logan)	9 Hours		
Average Tour of Duty		2.7 Days	
Occupation = Flight Crew			25%
= Executive/Managerial			10%
= Professional/Technical			9%
= Administrative Support/Clerical			7%
= Sales/Service			25%
= Production/Crafts			5%
= Maintenance/Trade			13%
= Cargo, baggage, drivers, ramp/ramp service			5%
Average Weekday Employees:	8,588	982	9570
Have more than 15 minutes of flexibility in schedule	21%		16%
Parking Subsidized by Employer			85%
Subway Commute Subsidized by Employer			3%
Commute Mode = Auto:			88%
" " " " and parking subsidized by employer			92%
" " " " and available autos ge number of adults in household			69%
Commute Mode = Subway:			10%
" " " " and parking subsidized by employer			46%
" " " " and available autos ge number of adults in household			19%

available to Logan employees do not compete very well with the automobile, and collectively attract only about 12 percent of Logan employees.

Geography

The concentration of employee origins is very different from the concentration of air passenger origins; more than 50 percent of employees originate from the corridor immediately north of Logan Airport, compared to 10 percent of air passengers. About 45 percent of air passengers begin their trip to the airport either from Boston or the corridor west of Boston, compared to 10 percent of employees. To further accentuate the differences in passenger and employee origin densities, the ratio of passengers to employees traveling to Logan on an average weekday is about three to one. Scheduled bus and limousine routes serving Logan were developed based on air passenger origins, and do not serve a large employee market. Table 2 is a comparison of air passenger and employee concentrations by geographic zones, and Figure 2 is a map denoting the zones.

Hours of Operation

For Logan employees with at least one trip end outside normal business hours, schedules developed around air passenger or commuter peaks often do not offer the frequency of service or hours of operation necessary to provide a reasonable commute. Figure 3 is a comparison of Logan employee arrival and departure times on an average weekday.

Travel Time

The door-to-door commute time to Logan on some scheduled services is not competitive with the automobile, due to the transfers required to complete the trip or to multiple stops and layovers built into a trip.

Multiple Stops and Layovers

The primary market for most of the privately operated bus routes is the downtown commuter. Offering the additional 2-mi trip to Logan is a low-cost method of filling otherwise empty seats. As such, travel times are minimized for commuters, and airport passengers experience longer travel times. On the way to Logan, commuters are first discharged at one or two locations in downtown Boston. Depending on traffic levels, travel from Logan to downtown Boston can take from 10 min to an hour. Because of the uncertainty of the travel time between Logan and downtown and the necessity to meet the evening schedule for commuters, the layover in Boston may be as long as an hour for an airport user departing Logan. On the way into Boston, a private bus route may stop in several towns to pick up passengers. Multiple stops and potentially long layovers in downtown Boston may be acceptable to the occasional air traveler, but are not acceptable service characteristics for Logan employees.

Transfers

The subway system Massachusetts Bay Transportation Authority (MBTA) in the greater Boston area offers low-cost, frequent, con-

TABLE 2 Comparison of Logan Airport Employee and Air Passenger Origins by Zone

Zone	Location	Employees	Air Passengers
1	Boston	4%	21%
2	Inner Ring, North	47%	5%
3	Inner Ring, Northwest	5%	4%
4	Inner Ring, West Northwest	1%	8%
5	Inner Ring, West	3%	7%
6	Inner Ring, South	8%	3%
7	Outer Ring, North	8%	4%
8	Outer Ring, Northwest	5%	6%
9	Outer Ring, West Northwest	1%	4%
10	Outer Ring, West	1%	8%
11	Outer Ring, Southwest	1%	3%
12	Outer Ring, South	6%	6%
13	Other Massachusetts	4%	8%
14	Connecticut, Rhode Island	1%	2%
15	Maine, New Hampshire, Vermont	5%	9%
16	Rest of the World	0%	2%

Source: 1990 Employee Survey, Spring 1993 Air Passenger Survey.

Notes:

1. Represents employee and air passenger origins on the average weekday.
2. On an average weekday, there are about 27,000 air passengers traveling to Logan and about 9,600 employees traveling to Logan; ie, 3% employees is equivalent to 1% air passengers.

venient service to downtown travelers. It is connected to a network of bus routes and commuter rail lines. The routes are primarily geared to radial travel into downtown Boston, and travel becomes less convenient between points outside of downtown Boston, including Logan. There is only one direct subway line to Logan.

The airport MBTA station is located on the edge of Logan Airport, about 1 mi from the air passenger terminals. Massport offers free bus service between the station and the air passenger terminals. Although the bus headways are consistent with the subway schedule, this presents an additional transfer for subway users. The number of transfers varies between one and three for the airport subway user. Commuter rail users must make three transfers. The more transfers people are faced with, the less likely they are to use a service.

Fares

The fares of many of the privately operated high-occupancy vehicle services are too high for airport employees who commute on a regular basis. Generally the monthly commuting expense for the privately operated bus and limousine routes to Logan is consider-

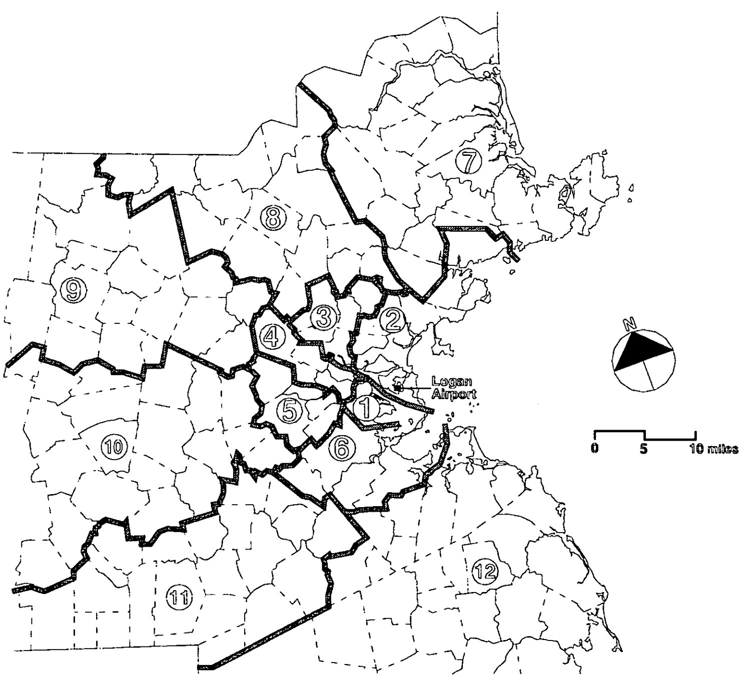

FIGURE 2 Geographic zones, eastern Massachusetts.

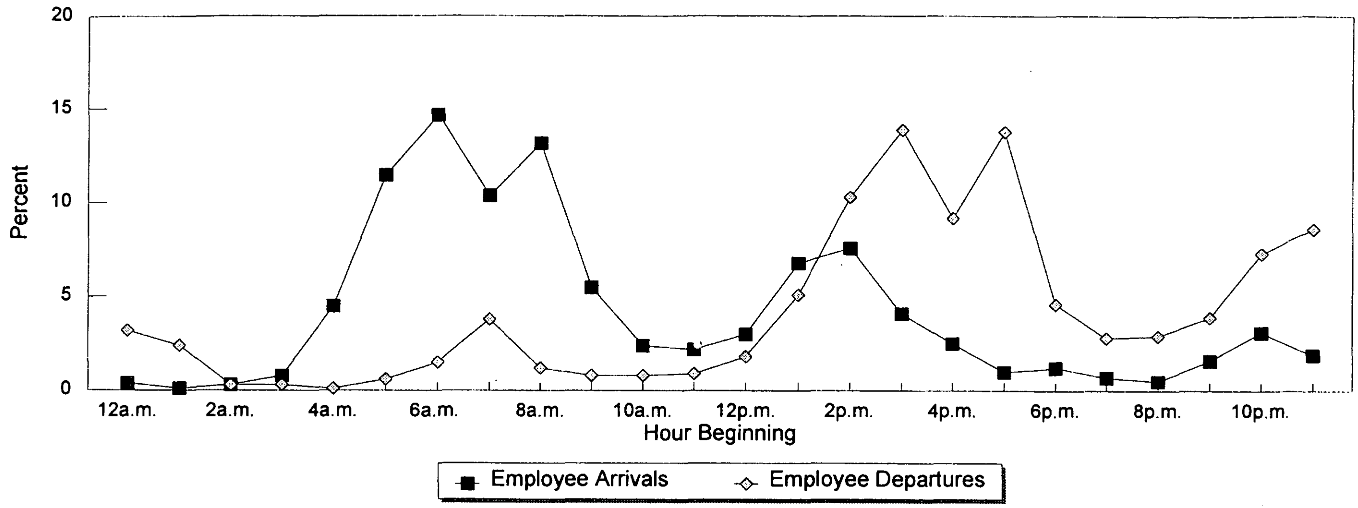

FIGURE 3 Logan Airport employee arrivals and departures by hour.

ably higher than the equivalent cost of services operated by the regional transit authority.

EMPLOYEE HIGH-OCCUPANCY VEHICLE INCENTIVES

Massport has been responsible for successful initiatives which have resulted in employees choosing alternatives to the private automobile. The following are the initial elements of our employee commute options program.

Incentives for All Airport Employees

Logan Express is a direct, non-stop bus service operated by Massport. The three routes serve remote locations, one about 32 kilometers west of the airport, one about 19 kilometers south of the airport, and one about 24 kilometers north of the airport. The services are operated daily, with weekday service at 30-min intervals from 5:00 a.m. until midnight.

Massport offers a discounted monthly Logan Express pass for all Logan Airport employees. The pass is priced slightly lower than the monthly rate for employee parking and is equivalent to between seven and nine one-way trips on the Logan Express. Ten-ride discount booklets are available for Logan Airport employees who don't find the pass to be economical. Employees using the service may park free of charge in the Logan Express parking lots. Taking advantage of the price incentive, employees of one airline convinced their employer to subsidize their Logan Express passes in exchange for their parking privileges. Several other airlines are now preparing to offer employees the option of a Logan Express pass or a subway pass in exchange for parking.

The number of employees using the Logan Express compares favorably to the concentration of employees in each of the market areas. In all, about 10 percent of employees reside in towns served by the three Logan Express routes. The most mature of the three routes captures about 25 percent of its employee market on an average weekday. On each of the routes, employees account for between 5 and 11 percent of ridership.

To further encourage employee ridership on Logan Express, beginning in January 1995, a 4:30 a.m. bus will be added on all routes to accommodate employees with early morning shift start times. Massport estimates that additional employee pass sales will cover about 40 percent of the incremental cost of the trip, and that additional air passengers using the service will cover another 50 percent of the cost.

The Airport Water Shuttle, a ferry service between Boston and Logan, offers a 60 percent discount for all Logan employees when tickets are purchased in 10-ride booklets. Some of the private high-occupancy vehicle services offer slight discounts to regular users or Logan employees. With the exception of those offered by a couple of private operators, the discounts are not deep enough to influence employee travel behavior.

As part of an effort to reduce employee vehicle trips through local neighborhoods, to comply with a federal and state regulation to reduce on-airport employee parking, and to increase air passenger parking, in August 1994 Massport relocated about 1500 employee parking spaces to a new parking garage one town west of the airport. A bus service transports employees between the airport and the garage. Massport estimates that some employees will switch to alternative modes of access rather than experience the inconvenience of driving to the remote garage to be bused to the airport. In fact, the airlines that are preparing to subsidize Logan Express passes or subway passes as an alternative to parking are doing so in recognition that alternative modes may offer an equivalent or shorter commute time compared to parking at the remote garage.

The remote garage is located in a town that has a high concentration of Logan employees. Since it is within walking distance of some residential areas, some employees may also use the bus as primary transportation to Logan.

Incentives for Massport Employees

Massport employees are subsidized for 50 percent of the monthly cost of commuting by subway, bus, commuter rail, and vanpools. The employee share of transit passes may be paid for through payroll deduction. For Massport employees commuting by Logan

Express or water shuttle, the 50-percent subsidy is applied to the cost of the already discounted monthly pass or 10-ride ticket booklet.

PREVIEW OF FUTURE PROGRAM DEVELOPMENT

In the upcoming months the following ideas will be further developed and evaluated, and some will be incorporated into a formal Logan employee commute options program. Because development of the formal program is in its early stages and is subject to discussion and collaboration with Logan Airport employers and within Massport, it is too early to provide great detail about the individual elements or cost of the program.

Ridematching Assistance

Current employee work hours and geographic considerations limit the potential for capturing large concentrations of employees in existing scheduled services. For the same reasons, the outlook for cost-effective new services is not good. In 1992 Massport conducted a survey of employees residing in a town with one of the highest concentrations of employees. Because the town does not have convenient access to public transportation, Massport considered initiating a shuttle bus network similar to a school bus network. Survey results indicated that, due to dispersed employee hours and residences, such a service would not be financially feasible.

Given the above conditions, along with current employment levels, carpooling may be a more realistic alternative for many airport employees. Massport is considering acquisition of a computerized ridematching program that enables employees to enter personal commute information directly into a data base by telephone, for temporary or part-time matching, or to become a permanent member of a carpool or vanpool. The program does not require personnel to assist in the matching. This would allow an employee to call a dedicated telephone number and communicate personal commute information using the telephone key pad. The information would be instantly processed, and the employee would be provided with ridesharing and high-occupancy vehicle alternatives. This would enable an employee with a varying schedule to participate in flexible carpooling, that is, as a part-time or temporary member of several carpools. Massport will also explore the potential for on-airport priority parking for those who choose ridesharing over single-occupant automobile access.

Logan Airport Transportation Management Association

Massport will probably provide some start-up funds for the formation of a transportation management association (TMA) among Logan employers. The TMA can then study and recommend additional elements for the employee commute options program. Massport believes that a program developed under a TMA will be more successful than a program developed by Massport, as participation in a TMA would demonstrate the employers' support of the commute options program. It would also allow an exchange of ideas among employers, including the insights of national companies who are dealing with employee commute issues in a variety of cities across the country. The TMA would facilitate the communication of common and different employee needs. Employers would be encouraged to determine individual employee needs through surveys or focus groups, and to share the results with the TMA. Initiatives and funding mechanisms could be developed collectively, through the TMA, or by individual employers.

A TMA would be an appropriate forum for encouraging employer subsidization of alternatives to single-occupant driving, and for encouraging flextime for employees when possible. Through a TMA, a guaranteed-ride-home program could be considered back-up transportation for commuters using alternatives to the single-occupant automobile. The guaranteed ride home would probably be available for employees in the case of an emergency or unscheduled overtime.

Additional potential elements that are likely to be studied by the TMA include the following: if potential passenger and employee demand is sufficient, working with some of the private bus operators to offer a limited amount of nonstop trips to Logan; encouraging private carriers to offer deeper discounts; and adding links to existing services. The level of ridership needed to support direct trips will vary by carrier due to different operating costs and revenues. Work with the private carriers on direct trips and fare reductions is more likely to be successful through a TMA, since operators have been skeptical of employee demand when approached by Massport about potential fare reductions.

Air Passenger Services

Massport is continuously exploring the potential for additional air passenger services. Any new service would capture some employees. Studies are currently under way for another Logan Express service and for alternative transportation options for passengers whose trips originate in high-density, close-in communities. The needs of these passengers would not be met by a traditional scheduled bus service. Massport may also provide a nonstop bus link between the airport and a downtown intermodal facility upon opening of the new cross-harbor tunnel in early 1996. The intermodal facility, called South Station, is located about three kilometers from Logan Airport, near the financial district. South Station serves as a collection point for all commuter rail lines south of Boston, intercity rail, and some public and private bus routes. A high-frequency bus link between Logan and South Station will eliminate two transfers for both subway and commuter rail passengers, providing a better level of service for all Logan users.

CONCLUSION

Major airports like Logan are large traffic generators, and are viewed by many as an easy target for trip reduction. But the trip-reduction strategies that may influence airport employees are different from what is thought of for typical commuters.

Airport employees are not as influenced by trip-reduction strategies as typical commuters because of their special scheduling needs, the availability of fully subsidized on-airport or near-airport parking, and other considerations specific to an individual airport.

Because the highest employee-origin densities in the greater Boston area are not in towns with a high density of air passengers, travel mode choices available to air passengers are not viable options for many Logan employees. Because employee work hours are dispersed over all hours of the day and week, it is currently not cost-effective for Massport to develop dedicated employee services, even for towns with a high density of employees.

A successful airport employee commute program will offer a variety of options to meet employee commuting needs. Flexible carpools may be a realistic alternative for many employees. Lower-cost initiatives that may accommodate some employees, such as flextime, where applicable, and a guaranteed ride home program, will make carpooling or vanpooling more attractive to employees.

Where feasible, existing high-occupancy modes may be made more accessible to employees by adding trips, offering reduced fares, or adding a limited amount of direct service on select routes.

Alternatives to the single-occupant automobile will become more attractive for employees if the supply of on-airport parking is reduced, particularly if on-airport priority parking is made available for carpools and vanpools. Alternatives to the single-occupant automobile will also become more attractive if employees become responsible for parking costs; however, this is unlikely at this time, due to collective bargaining agreements, nationwide airline employee benefits packages, and competitive employee benefits among airlines. Offering employees the cash equivalent of parking fees to be used for parking or for a less expensive alternative mode may also influence employees away from the single-occupant commute.

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