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Contents

Foreword

All but the final paper in this Record deal with planning, operation, or management of airports and airspace. The scope of interest covers a wide range—from regional and statewide planning concerns to design and evaluation of specific functional components of terminal buildings and airport landside approaches. The theme of these papers is that sound planning and management are crucial to successful operation of the airport and airways system and its surface transportation links, where success is defined as wise use of resources, economy of expenditure, and high-quality service to air travelers.

Caves examines methods to forecast traffic shares among small competing airports within a regional market. He concludes that a "step-down" forecasting method that includes a short-haul (intraregional) component, a charter traffic component, and a long-haul (extraregional) component is a valid and useful way to estimate future demand, provided the region is sufficiently free standing and there is little competition with airports in neighboring regions for air traffic.

Mumayiz and Hayter describe an airspace system analysis conducted as part of the site-selection study for a new regional airport in the Chicago area. They report the results of a simulation that evaluated operational characteristics and performance at the airport and system levels for five alternative sites.

Broten and McNeely discuss three management tools used by Virginia to identify obstructions on airport approaches, store information on airport physical features, and program airport pavement maintenance and rehabilitation. Computerized for ease and speed of information access, the tools provide a coordinated and systematic way to make decisions about management of Virginia's air transportation system.

Hassounah and Steuart employ a simulation model to estimate demand for aircraft gates. The results of the modeling exercise show that a strategy of nondedicated gates open to all on a first-come-first-served basis requires fewer gates than strategy that restricts gate use to a particular carrier or type of aircraft. Furthermore, for a scheduling practice involving connecting banks, the model demonstrates how the time interval between banks influences gate requirements.

Ndoh and Ashford examine how improvements to terminal services and facilities generate a need to make corresponding improvements in the level of service of the airport access system. The authors extend research in level of service evaluation of airport access to include psychometric techniques. The results, presented in terms of passengers' satisfaction with various access attributes, indicate the need for better distribution of access information to air passengers.

Models of passenger traffic flows at airport terminals and analogous models from other areas of engineering are investigated by Vandebona and Allen, who apply queueing theory to analysis of congestion, delay, and travel time. Passenger behavioral attributes, such as desire to reach the terminal with time to spare and apprehension about missing flights, are taken into account.

Poor and Stewart observe that recent designs of automated people-mover systems employing small three-person vehicles (personal rapid transit, or PRT) present urban planners and developers with a new option for meeting transportation needs. The authors distinguish PRT from other fixed-guideway people movers already in use at Seattle-Tacoma International Airport and discuss some of the complications that would arise in introducing PRT technology into a real urban environment.

The final paper by Barnett deals with a completely separate topic: the reliability of statistical inferences that can be drawn from data on rare events, in this case fatal air crashes. The author's argument is that, although small data samples present difficult and intricate problems of statistical inference, they are not as unreliable or lacking in value as many researchers have concluded.

Forecasting Traffic at Smaller Airports in a Free Market Environment

ROBERT E. CAVES

Many small airports in the United Kingdom are competing for traffic. Ideally, forecasts for these airports should be made by applying behavioral models of airport choice to national forecasts. Although the U.K. Civil Aviation Authority has attempted this approach, it is difficult to retain sufficient accuracy to deal with the smaller airports. A two-stage method of analysis has been proposed that combines the simplicity of a "step-down" method with the accuracy of discrete choice models. The stability of regional shares of national traffic has been demonstrated for subcategories of traffic. The adequacy of discrete choice models to predict local airport shares, when applied to traffic generated within a region, has also been demonstrated by means of a case study. The two-stage approach is therefore recommended for consideration by airports wishing to determine their potential traffic in a competitive market.

It is usually straightforward to predict future traffic levels at well-established airports with clearly defined roles within a stable regulatory framework, although they can be subject to the impact of political events and fluctuations of the economy. Traffic prediction becomes progressively more difficult as air transport regulation is liberalized, thereby increasing the possibility for the airport's role to change, and as airport privatization encourages airports to seek expanded roles. The difficulties are further aggravated when the airport is small and its role is determined not only in relation to the local population but also by interactions with other airports within a region. This is the situation facing several U.K. airports. The generic diagram (Figure 1) indicates that small local airports wanting to expand their role have to compete with larger nearby regional and national airports and also with emerging (but currently small) airports situated close to the capital. The emerging capital city airports themselves have to compete with each other and with the capital's major airports.

Experience with the U.K. airport system shows that, in the absence of major initiatives, airports that are initially favored by geography or the regulators are the first to develop a range of services. Once they have a market advantage, the advantage is augmented because airlines are attracted to busier markets and passengers perceive the benefits of increased frequency. This logic leads to the well-known "S-curve" effect, whereby the airport with the major frequency share captures an even greater share of the traffic (*1*). In many cases, even when a service might have been justified at a smaller airport, the airline has adopted a cautious approach to marketing and to the supply of capacity and frequency, which results in a revealed preference by passengers for better (and probably less expensive) service at the expense of longer access trips. Deregulation, by enhancing the availability of lower fares at points of concentrated service (*2*), tends to increase the S-curve effect.

In summary, future traffic at small airports will be influenced strongly by the local economy and the ensuing passenger demand, but also by

- Historic airport hierarchy,
- Regulatory opportunities for carriers and the airport,
- Marketing and investment decisions by competing airports, and
- Airline decisions to mount feeder or hubbing services and the quality of the resulting service.

These factors are diverse and appear to be influenced primarily by policy decisions largely outside the control of a local airport's management. It is therefore tempting to adopt one of two extreme approaches to the prediction of traffic at smaller regional airports.

On one hand, it may be considered impossible to cope with the external uncertainties except by judgment, with the emphasis then being on historic traffic trends and the econometrics of locally derived demand as practiced in traditional airport master planning. This method will call for assumptions about the level of service and the resultant market share if the projected enhanced role of the airport is to be reflected in the traffic predictions, even if substantial potential demand is shown to exist.

On the other hand, the airport may recognize that its future must be codetermined with the other airports in the national system and call for a national traffic distribution model that would be responsive to airline strategies at all competing airports. Any such model would need inputs to describe capacity and regulatory constraints and would need to model demand and supply simultaneously, so that both airline strategic decisions and the other airports' competitive marketing would be determined endogenously.

NATIONAL AIRPORT COMPETITION MODEL

The U.K. Civil Aviation Authority (CAA) has developed a model that predicts total U.K. traffic and the distribution of the traffic between London and the regions (*3,4*). The CAA model was developed primarily to study the distribution of traffic among airports in the London area and to estimate the regional airports' share of total U.K. traffic using logit models calibrated on an extensive survey of individual trips. The abil-

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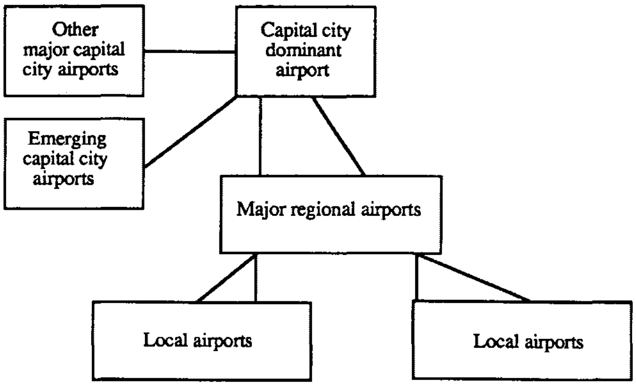

FIGURE 1 Generic relationships among U.K. airports.

ity of the model to determine individual shares for the smaller regional airports (a task for which it was not designed) is examined in detail elsewhere (*5*). Supply is addressed by calibrating a separate model of airline behavior in terms of aircraft size and operating frequency for a given traffic density. The model has potential weaknesses in the exogenous determination of the airports' attraction factors in the long-haul and domestic models. In addition, the origin zones in the regions are large compared with the distance between competing airports, and there is no allowance for increases in local demand as quality of service is increased owing to either inward job migration or increased propensity to fly.

An indication of the extent to which changes in model specifications and airport capacity assumptions can induce large changes in predictions for smaller regional airports, while having a much smaller proportional effect on the London area airports, is shown in Table 1 for two airports in the Midlands. Birmingham (BHX) and East Midlands (EMA) are both approximately 100 mi northwest of London. They are two of the regional airports closest to London and are 40 mi apart with similar runway lengths. The table gives the results of two attempts by CAA to predict regional airport traffic. The earlier attempt was published in CAP 548 (*3*), which considered four options for the possible expansion of the London area airport system; only Cases 2 and 4 are pertinent here. A later attempt was published in CAP 570 (*4*), which considered several London area options, of which only the Base and Heathrow (LHR) expansion cases are pertinent here. The four London airports considered were Heathrow, Gatwick, Stansted, and Luton.

The scenarios examined were the following:

- Case 2: assumed Heathrow, Gatwick, and Luton capacity limited at 55, 30, and 5 million passengers per year (mppa), respectively, but Stansted able to take full London area demand (33 mppa).
- Case 4: assumed capacity limits at all London area airports, including 20 mppa at Stansted.
- Base Expansion: assumed capacity limits of 50, 30, 30, and 5 mppa at Heathrow, Gatwick, Stansted, and Luton, respectively.
- Heathrow Expansion: assumed the full demand of 86 mppa at Heathrow could be met with no other airports reaching capacity.

Case 2 from CAP 548 and the Base case from CAP 570 are similar scenarios. A comparison of their traffic predictions shows how the model specification changes adversely affected East Midlands' predicted traffic and substantially increased Birmingham's long-haul traffic. These changes in the model specification were mainly to the long-haul attraction factors exogenously assigned to the airports. In effect, these attraction factors imply that the distribution of traffic is supply driven, at least while there is an overall shortfall in supply in the regions to cater for regional demand.

In comparison, the differences in predictions between Case 2 and Case 4 of the CAP 548 model and between the Base and Heathrow expansion cases of the CAP 570 model show the model predictions of spill of traffic to the regions as a result of shortages of capacity in the London system. The implications of these results are that changes in regional traffic predictions at individual airports due to changes in model specification are at least as great as those due to capacity limitations.

TABLE 1 Prediction of Airports' International Passengers by CAA (millions)

	Year 1988	Year 2005 from CAP 548		Year 2005 from CAP 570	
		Case 2 (a)	Case 4 (b)	Base (c)	Heathrow expansion (d)
East Midlands					
Short haul	1.0	4.5	6.5	3.1	3.1
Long haul	0.0	0.4	3.1	0.0	0.0
Birmingham					
Short haul	2.2	7.3	8.7	6.0	5.1
Long haul	0.0	0.5	3.9	6.3	2.2
Total Non-London					
Short haul	15.9	39.2	42.5	39.3	35.9
Long haul	1.9	1.6	9.1	17.2	10.6
Total London					
Short haul	36.9	69.7	65.0	63.8	68.5
Long haul	16.7	40.2	32.0	35.5	44.5

It appears that a full national model of traffic generation and distribution, incorporating the smaller airports, would be difficult to calibrate with sufficient accuracy. It would also be difficult to retain sufficient flexibility to cope with individual regional characteristics. However, the CAA model has been developed on a data base obtained from surveys (*6*), which sample approximately 2 percent of departing passengers at most U.K. airports on a 3- to 4-year cycle. Information is collected on socioeconomic characteristics, journey origins, access modes, trip purpose, airports used, and other data. So many data of individual travel are available from the CAA surveys that a more limited use of an airport choice model within each region, or between each region and national hub airports, could contribute considerable accuracy to regional airport traffic estimates. Although it may be possible to develop a satisfactory behavioral model to share regional traffic between the local airports and large national airports, in practice this has proved difficult (*7*). Problems are likely to arise with any particular continuous form of frequency function. The high frequencies at large airports are likely to mean that passengers will be less responsive to a given percentage or absolute change of frequency at these airports than at smaller airports with only one or two services per day. There are attractive and unattractive features of large airports, apart from the services to specific destinations, which are difficult to model convincingly, particularly because they vary over time. Added attractions include the synergy of large networks, choice of airlines, shopping opportunities, and availability of official and unofficial discounts. Conversely, congestion inside and outside the airport is unattractive.

HYBRID MODEL APPROACH

The alternative approach is to take advantage of any stability in the national and regional situation to establish regional shares, reserving the rich information derived from discrete airport choice models for local airport competition. Stable relationships between national and regional traffic can form the basis of a step-down approach to modeling regional traffic, given the existence of uncontroversial national forecasts. These are available in the United Kingdom, disaggregated by business or leisure, short or long haul, U.K. or foreign (*8*). Although subject to any forecasts' imperfections, CAA's forecasts offer a consistent base from which to develop a feasible range of national forecasts.

Step-Down Element

An attempt has been made to establish the reliability of the step-down approach to forecast U.K. regional and individual airport traffic at a less aggregate level (*9*). The analysis separately considered international short-haul scheduled and charter traffic to each of the primary destinations in each category and also the aggregate traffic at each airport and in each region. Three reasonably well-defined regions were chosen in addition to the London area: the Northwest (NW) with Manchester (MAN), Leeds-Bradford (LBA), and Liverpool (LPL) airports; the Northeast (NE) with Newcastle (NCL) and Teesside (MME) airports; and the Midlands (MID) with Birmingham (BHX) and East Midlands (EMA) airports. In the traffic categories examined there are few airport access trips between these regions, although there is substantial use of London area airports by passengers with ultimate origin or destination in these regions. The analysis is based on annual traffic from 1982 through 1989. Airport traffic and international route traffic data are taken from CAA's Annual Airport Statistics and domestic route data from the Annual Airline Statistics. The international scheduled destinations considered are Paris (CDG), Amsterdam (AMS), Dublin (DUB), and Frankfurt (FRA). Charter destinations are Malaga (AGP), Palma (PMI), Faro (FAO), and Corfu (CFU).

Shares of Total Boardings

All three regions' total traffic shows strong statistically significant linear relationships with total U.K. traffic in each traffic category. When the regional shares themselves are regressed against U.K. traffic (thus increasing the sensitivity of the analysis), the NW region is shown to be increasing its share of international scheduled traffic at the rate of 1.09 percent per 10 million U.K. passengers (5 percent in 1989) and its share of charter traffic at 3.4 percent per 10 million passengers (23 percent in 1989). The Midlands region's growth in U.K. share is 0.48 percent (2 percent in 1989) and 0.85 percent (9 percent in 1989) per 10 million U.K. passengers for international scheduled and charter traffic, respectively. The results of this analysis are given in Table 2. The relationship is

$y = a + bx$

y = regional share of passengers

x = U.K. passengers (millions)

The t statistic > 1.94 indicates 10 percent significance,

> 2.45 indicates 5 percent significance, and

> 3.71 indicates 1 percent significance.

It can be seen that the NE region traffic shares calibrate much less well in terms of R^2, and the relations with U.K. traffic are weak. However, the NE constant terms are significant, indicating that its shares of scheduled and charter traffic are remaining constant at 0.38 percent and 3.4 percent, respectively.

It is noticeable that there is a much higher penetration of charter into the regions than of scheduled services. Although this may be explained in part by the easier acquisition of charter route rights, the main reason is likely the charter airlines' ability to control load factors in the lower-density markets by offering relatively low capacity. This is not available to scheduled airlines on most routes at reasonable fares because low levels of service drive down the demand for direct service. The resultant higher fares drive down demand further.

It is also noticeable that NW and MID shares of U.K. traffic are increasing at approximately the same relative rate, whereas NE shares are constant. These trends result from longer-term trends in the economies of the regions and the airlines' responses to the potential market. Success appears to breed

TABLE 2 Relationship Between Traffic in U.K. Regions and Total U.K. Traffic

	100a		100b		R^2
	Value	't'	Value	't'	
International Scheduled					
NW	-0.167	-0.34	0.1090	8.15	0.917
MID	-0.0407	-0.15	0.0484	6.47	0.875
NE	0.377	6.07	-0.0002	-0.09	0.001
Charter					
NW	13.30	10.80	0.340	6.26	0.867
MID	6.49	6.87	0.085	2.03	0.408
NE	3.39	8.56	-0.0009	-0.49	0.038

The constants are defined by the equation in the text.

success once a viable minimum network of routes can be supported. It may well be that success comes not only from increasing economies of station density but also from stimulated demand, with stimulated demand coming from the release of latent demand among the existing population as their total disutility of travel falls and also from demand induced as new economic activity is drawn to the improved services. Anecdotal and empirical evidence indicates that improved supply stimulates demand (*10*).

The step-down method implicitly incorporates these effects. The method clearly cannot distinguish between the factors causing the changes of regional share and presumes that the regional economies and airline reactions will continue to change in the same direction at the same rate. There may, of course, be long-term changes in regional status, the effect of which would have to be treated judgmentally, but, in general, the relative economic changes in any well-defined region are quite stable.

There may be, however, the possibility for individual airports within a region to influence their competitive position or role. Individual airports' rates of change of national traffic share are given in Table 3 for all the sampled airports that showed statistically significant relationships at the 5 percent level. The major airport in NE is NCL, but correlations for NCL traffic were not statistically significant (1989 passengers: 0.17 million international scheduled, 0.80 million charter). In almost all cases, the individual airport shares are rather less predictable than the total regional share of national traffic. In every case, the minor airports' shares grow less rapidly or fall faster than the major airports' shares in each region and their statistical explanation is worse than the major airports' shares.

Because the regions do not, in general, encompass areas of more than 2 hr access travel time by car, it is possible that smaller airports could gain share if they could induce a change of attitude by the airlines. Otherwise, a direct step-down analysis shows that all the smaller airports are likely to capture a decreasing share of regional traffic. Indeed, in the case of MME, there is a statistically robust falling national share. These trends are reinforced by an analysis of the small airports' share of the regional markets. The statistical fit of the NW airports' shares is poor; the MID and NE airports' fit is much better but still gives R^2 of less than 0.7. Thus, even if the smaller airports were prepared to accept the implications

TABLE 3 Regional Airports' Growth in Share of U.K. Traffic (percent per million U.K. passengers)

		% change	1989 passengers (millions)
NW International Scheduled			
	MAN	0.0963	2.21
	LBA	0.0068	0.16
	LPL	0.0056	0.12
NW Charter			
	MAN	0.3220	5.93
	LBA	0.0248	0.25
MID International Scheduled			
	BHX	0.0457	1.03
	EMA	0.0027	0.14
MID Charter			
	BHX	0.0781	1.57
	EMA	Indeterminate	0.92
NE International Scheduled			
	MME	- 0.0014	0.02
NE Charter			
	MME	- 0.0081	0.06

of declining market share, the statistical quality of the second stage of a two-stage step-down model does not allow much confidence in its use.

Shares of Route Traffic

The step-down analysis has been concerned so far only with total traffic growth at a regional airport in a given category. The total traffic growth, in fact, consists of growth per route and also new route starts. The growth per route can be analyzed on a step-down basis. It would be expected that, as the regional penetration of the national market matures, the growth in share would tend asymptotically to zero. The market share at the point of zero growth would be the maximum likely penetration, reflecting the best likely supply of direct service from the region whether concentrated at the main airport or shared between airports. The average growth in share (i.e., growth in total traffic at a given airport) would tend to be greater than growth on mature routes because of the higher growth in share on emergent routes and the addition of new routes.

When this analysis is carried out for four of the most common destinations in each traffic category, the growth in share is inevitably seen to be variable with rather poor statistical significance. By taking the international scheduled category first, the NW route shares indeed show much lower growth than its share in the total traffic, and the intercepts' t-tests are robust, implying maturity on these dense routes. However, the MID shares to the same destinations are still growing strongly and robustly, indicating that maturity of penetration has not been reached even in the densest markets. Estimates of the average maximum U.K. market penetration for mature routes is given in Table 4. These estimates provide a cut-off point when growth in market share is used for prediction. The growth in total share is actually lower than the average growth in the four top markets because one of the top markets performed poorly. Even the top markets from most regions are rather fragile. This suggests that it would be optimistic to take the penetration of the densest markets as indicators of likely long-term penetration. In the NE, there is actually negative growth in share to two of the three destinations, because of historically established, artificially high penetration of the market to AMS due to Air U.K.'s route network.

In contrast to the scheduled routes, all the top charter destinations from all the regions appear to have reached mature shares: all the regressions show low and statistically insignificant growths in share, the R^2 is small, and the intercept t-tests are robust. Despite this maturity on the densest routes, the rate of growth in share of total charter traffic in NW and MID is considerably greater than for the total scheduled traffic (Table 2), indicating the importance of new charter route starts in the regions. This relative paucity of destinations from the regions is likely to continue into the medium-term future; if total rather than route-by-route market shares were to be used for prediction, some estimates would have to be made of the maximum likely penetrations of the total U.K. market that would be lower than those reported in Table 4.

Attempts to analyze the smaller airports' shares of their regional markets on a route-by-route basis fail to establish consistent patterns or statistically significant correlations. However, inspection of market shares over time indicates a consistent tendency to converge to values that reflect the historic balance between the attractions of the major regional airport, the spatial distribution of demand, and the airlines' supply strategy. The resulting estimates of likely maximum minor airport shares are given in Table 4.

Airport Choice Element

Although it is unlikely that the balance between regional and national interests will change other than slowly and predictably regardless of airport and airline managerial initiatives, this is less true of the balance between airports within a region. It would be possible to attract airlines and passengers by investment in improved facilities (e.g., extended runways, provision of airbridges, and competitive fuel tendering). There is also the possibility of changes of spatial economic distribution within a region, of airlines setting up competing services (possibly even a hubbing operation) without head-on competition from an incumbent airline at the major airport, of there being an easier environmental or land use situation for expansion at the minor airport, or of the major airport approaching capacity so that lower-cost airlines begin to be displaced. An analysis of the implications of any of these scenarios for the smaller airports cannot rely on the step-down approach, which, by definition, assumes that the factors that are already changing will continue to change at the same rate and no new factors will enter the situation.

Certainly, there is room within the market share method for some exercise of judgment to allow for limited change, but it would be risky to rely only on that when major changes in the role of an airport are anticipated. In these circumstances

TABLE 4 Estimates of Maximum U.K. Market Shares on Mature International Short-Haul Routes

	Total Regional Flow, 1989 (millions)	Regional Share of UK Total	Minor Airport Share of Regional Total
NW Scheduled	2.5	0.12	0.20
NW Charter	6.3	0.25	0.10
MID Scheduled	1.2	0.07	0.30
MID Charter	2.5	0.13	0.45
NE Scheduled	0.2	0.01	0.20
NE Charter	0.9	0.05	0.18

the analysis of intraregional competition requires a modeling tool sensitive to local spatial changes in demand patterns, access times, and the supply of service on a route-by-route basis. In other words, a local version of CAA's airport choice model with local demand a function of air service available would be a feasible approach. Despite some reservations about the choice of independent variables in the utility function, similar logit models have been used to good effect in many studies (*11,12*). Other U.K. uses of the model are referred to elsewhere (*5*).

Just such a model has been developed for trips by short-haul scheduled services from the Midlands region where BHX is the major airport and EMA is the minor airport (*13*). A CAA survey of passengers at the region's airports was used to define the set of approximately 100 zones from which passengers might travel to use the region's airports and to identify individual trips to a set of destinations jointly served by both airports (*6*). These trips were used to calibrate a standard logit model whose utility function took the following form:

$$U_{ijm} = aA_{ij} + bF_j + cP_j$$

where

A_{ij} = access time (min) for a passenger in zone i to airport j,
F = share of weekly flight departures for airport j (i.e., departures at j/(departures at $j + k$),
P = full economy fare from airport j to destination m (£ sterling),
U = utility of a passenger in zone i using airport j to reach destination m.

Separate models were calibrated for business and leisure passengers, each to the same four high-volume destinations. The calibrations were successful in each case. The fare variable added no additional explanation in the business model and was dropped when the model was used for prediction.

The utility function in the business passenger model, based on 1,525 observations, was calibrated as

$$U = -0.0757A + 8.695F$$
$$(-19.7) \quad (11.8)$$

The values in brackets denote the t-test results. The leisure passenger utility function, based on 720 trips, was found to be

$$U = -0.0769A + 4.898F - 0.0808P$$
$$(-14.7) \quad (3.1) \quad (-3.0)$$

The signs and relative sizes of the coefficients are all in agreement with intuition. Frequency is more important to the business traveler, and cost is the predominant concern of the leisure passenger. This is borne out by the utility functions when average values of 30 min, 0.5, and £90 are substituted for A, F, and P, respectively. (£1.00 is approximately equal to U.S. $1.70 during the period under analysis.) The implied direct elasticities, averaged over BHX and EMA airports, are

A −0.59 for business, −0.52 for leisure;
F 0.62 for business, 0.30 for leisure; and
P −0.73 for leisure.

Because leisure passengers will have paid perhaps only 50 percent of full economy fares, their real fare elasticities are probably nearer to −1.4.

In view of the small differences in fare and frequency between BHX and EMA (Table 5) on the four jointly served routes in the 1983 calibration year, the coefficients are surprisingly reasonable and intuitively correct. All EMA services were operated by British Midland with turboprop aircraft, and the BHX services were almost exclusively operated by British Airways (BA) using BAe 1-11 jets. The market shares to EMA in 1983 from the observed set of zones were 29 and 49 percent for business and leisure passengers, respectively.

Although the model fit the 1983 data well, it was not so successful when predicting 1987 market shares. By then, EMA had only approximately a 33 percent frequency share because of more airlines serving BHX, although not always with jet service. This resulted in an actual average market share to EMA of 30 percent on routes served twice a day; CDG obtained 17 percent on a once-daily service. The models overpredicted these shares by 7 percent.

The discrepancy could be because of a misspecification of the frequency function, either in its nature (e.g., ratio or difference instead of share) or in its shape (e.g., log or exponential instead of linear). It is also true that the situation changed substantially between 1983 and 1987. In favor of East Midlands subregion, there was differential growth in population and the economy relative to the West Midlands subregion. The increased service at BHX was mostly by foreign airlines and with turboprop aircraft. Furthermore, British Midland began to establish an image as an international airline as well as being able to compete with BA on the major domestic shuttle routes from Heathrow. In favor of Birmingham, an impressive new BA terminal was opened in 1984, and the introduction of new destinations began to create a hubbing synergy. Unless the model's frequency function is in error, it appears that the changes favoring EMA have had a greater effect than those favoring BHX. A short-term expedient is

TABLE 5 Air Services Offered in 1983 at Birmingham (BHX) and East Midlands (EMA) Airports

	Frequency per week		Full economy fare (£)	
	BHX	EMA	BHX	EMA
AMS	13	12	87	87
CDG	12	6	116	95
GLA	10	10	66	54
BFS	13	10	56	54

therefore to adjust the model with a positive constant (dummy) for EMA. When this is done and the model is used to investigate the effect of changes in airline policy and access routes, it suggests that if EMA services matched BHX frequencies EMA would take approximately a 50 percent share of the market from the zones selected, even without a matching jet service. This is owing to the lower density but spatially larger natural catchment area of EMA. Furthermore, improvements to the roads linking the two airports favor EMA at equal frequency because the dense Birmingham population then becomes available, whereas less of the natural catchment area of EMA is vulnerable to BHX. The model suggests that reducing the trip time between airports from 50 to 40 min, as happened in 1991, increases EMA's market share at equal frequencies by some 5 percent.

Work is ongoing to improve the frequency function and include flight timing and examine the implications of closely timed flights. Other areas under further investigation are nationality mix of the airlines, aircraft technology, and importance of fares, using new data on fares actually paid. In addition, there are indications that, although it is not possible to calibrate a nationwide model to give sufficient accuracy at local airport level, it may be possible to develop a model to distribute traffic from a defined region simultaneously between the major airports and the local airports by careful specification of the frequency function. This would call for the step-down method to be applied directly to trip generations in a region instead of to the trips revealed through the region's airports. The differential growth in regionally based trips would be established through the ongoing series of CAA surveys.

CONCLUSIONS

The step-down procedure for forecasting regional airport demand was investigated in a U.K. case study. The approach is shown to be valid when it is possible to define regions sufficiently free standing for there to be little interregional competition for air traffic. It has been shown that, where substantial competition between airports exists within a region, the step-down procedure is inappropriate to define market share within the region even when status quo assumptions can be made. When it is necessary to analyze the implications of new competitive scenarios, it has been shown that logit models can be used to distribute intraregional demand between airports in response to changing quality of service. It is, of course, not possible within that methodology to predict the extent to which airlines will provide that quality of service. The step-down procedure can still provide the total regional traffic predictions as an input to the logit models, although more work is necessary to account for the effects of improved coverage of supply within a region on the regional share of U.K. traffic.

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Analysis and Simulation of Regional Airspace

S. MUMAYIZ AND S. HAYTER

The Chicago-region airspace system analysis conducted as part of the site selection phase of the Illinois-Indiana Regional Airport study is described. The analysis provided data on performance measures used to evaluate the five proposed alternative sites, from the airspace feasibility standpoint. A comparative analysis approach considering alternatives and scenarios was conducted using data generated from SIMMOD simulation. The region, nature of study, structure and characteristics of the region's airspace, elements of the analysis methodology, input data requirements and collection, simulation procedure, and interpretation of simulation output data are described and discussed. The performance measures used as criteria to assess the feasibility of the alternative airport sites from regional airspace system are discussed. Results of the analysis are presented, evaluation of performance measures on the airport and system levels are discussed, and the operational characteristics of the regional airspace system with each of the five alternative sites included are described.

The Chicago region defined by the study consists of nine counties in northeastern Illinois (Cook, Kane, Lake, McHenry, DuPage, Will, and Kankakee) and northwestern Indiana (Lake and Porter) (*1*). According to the National Plan for Integrated Airport System (*2*), the Chicago region (air traffic hub) consists of two primary airports (O'Hare and Midway), nine reliever airports, and five general aviation airports (see Table 1). Several of the region's public airports are included in the FAA Terminal Area and Hub Forecasts for Chicago (*3*).

The air traffic activity in and around the Chicago area is extensive. O'Hare is the busiest airport in the world and is a major U.S. hub for the United States' two largest airlines—American and United. The regional air traffic system is the crossroads of the east-west air traffic of North America. The sheer number of flights into and out of the airspace system dictates and limits the options available in the designing of necessary airspace modifications and the procedures required to accommodate a new major airport in the area. Table 2 lists aviation activities at some of the Chicago-area airspace air traffic control (ATC) facilities, the daily average, and their ranking in the United States. Chicago Air Route Traffic Control Center (ARTCC) and O'Hare Air Traffic Control Tower (ATCT) are the busiest in the United States, with daily average aircraft operations of 6,847 and 2,163, respectively (*4*). O'Hare Terminal Radar Area Control center (TRACON) is the second most active in the U.S. National Airspace System (NAS) with 3,233 average daily aircraft operations during 1989.

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STUDY

The Illinois-Indiana Regional, or the Chicago Region Supplemental, Airport is the largest new airport development planning effort since Dallas–Fort Worth Regional Airport. The main objective of the site selection phase of the study, sponsored by the states of Illinois and Indiana and the city of Chicago, is to research factors relevant to selecting the site for a new major air carrier airport in the southern part of the greater Chicago area. The sites the study investigated are

- Gary Regional Airport, Gary, Lake County, Indiana;
- Lake Calumet site, Chicago, Cook County, Illinois;
- Peotone Site, near Peotone, Will County, Illinois;
- BiState Site, between Beecher, Will County, Illinois, and Cedar Lake, Lake County, Indiana; and
- Kankakee site, North of Kankakee, Kankakèe County, Illinois.

The location of these five sites in the Chicago region and in relation to O'Hare International Airport is shown in Figure 1.

From an airspace standpoint, the feasibility of establishing another major airport in the Chicago area is largely dependent on the ability of the ATC system to accommodate the increased demand that a new airport's activity will impose on available airspace. The determination of feasibility must therefore be based on quantitative data that support the premise that an additional airport can fit harmoniously within the greater Chicago area and can coexist with other airports without compromising air safety, operational efficiency, and existing capabilities of the region's airport system. However, with the region's aviation demand forecast likely to exceed available capacity soon, this objective may be difficult to attain. Some of the conditions stipulated in the study require the new proposed airport to augment existing capabilities and not introduce an airspace environment that compromises the existing level of safety. Furthermore, air safety cannot be addressed independent of considerations of operational efficiency. If a proposed site dictates maintaining safety through the inordinate application of various techniques for accommodating the increased demand on the region (such as airborne and ground holding, delay or diversion routing, and increased separation intervals), the site's candidacy as a new major airport is suspect. In considering these criteria, the predicted activity of each existing airport within the greater Chicago area must be considered as well as that of the proposed airport. From an airspace perspective, the proposed airport should serve to ameliorate the capacity problems at Chicago's major airports without unduly diminishing the ca-

TABLE 1 Chicago Region System Airports (1989) (*2*)

Airport	Classification[1]	Based GA Aircraft	Demand, Aircraft Operations	Nominal Capacity (ASV[2])
Chicago O'Hare International[3]	PR_L	2	797,000	841,000
Chicago Midway[3]	PR_L	292	257,000	330,000
Lake in the Hills[3]	RL_BU	136	94,000	108,000
Waukeegan Regional[3]	RL_TR	261	131,000	220,000
Palwaukee[3]	RL_TR	460	207,000	275,000
Aurora Municipal[3]	RL_TR	276	146,000	160,000
DuPage County[3]	RL_GU	470	217,000	160,000
Lewis University (Romeoville)[3]	RL_BU	243	74,000	155,000
Lansing Municipal	RL_BU	158	39,000	155,000
Gary Regional[3]	RL_TR	115	106,000	220,000
Chicago Meigs Field[3]	CR_S	4	6,000	240,000
Clow (Plainfield)	GA_BU	141	37,000	150,000
Schaumburg[3]	GA_BU	141	83,000	215,000
Campbell (Round Lake Park)[3]	GA_GU	90	18,000	220,000
Joliet Park[3]	GA_BU	81	59,000	215,000
Frankfort	GA_BU	162	38,000	150,000

Notes: (1) P= Commercial Service-Primary (L=Long-Haul, M=Medium-Haul, S=Short-Haul), CM= Commercial Service-Other, CR= Reliever Airport with Commercial Service, RL=Reliever (GU=general utility, TR=transport, BU= Basic Utility), GA= General Aviation.
(2) Annual Service Volume, in terms of aircraft operations
(3) Airports included in FAA Terminal Area Forecasts

pability of an existing facility. The proposed airport must therefore provide the capability to meet or exceed the increased demand forecast.

In establishing the ground rules for an airspace study of the magnitude of the Illinois-Indiana Regional Airport Study, considerable thought was given to past studies, the results expected, and a means of quantifying and measuring the outcome against known and established facts. The study team determined that to arrive at reasonable and valid conclusions regarding the impact of an additional major airport in the Chicago area, as much as possible of the total Chicago ARTCC airspace should be included in the study (*5*). It is also determined that a distance of 150 nautical miles (NM) from O'Hare airport would encompass most of the airspace pertinent to the study objectives. Problems involved with the integration of arrival and departure operations to and from the Chicago airports with high-altitude en route traffic are resolved outside this 150 NM airspace radius or resolved through traffic man-

TABLE 2 Air Traffic Operations in Chicago Airspace (Total Aircraft Operations) (*4*)

Facility	Annual Operations	NAS Rank 1989	Daily Average Operations
Chicago ARTCC	2,499,252	1 (ARTCC)	6,847
Chicago O'Hare TRACON	1,179,889	2 (TRACON)	3,233
O'Hare ATCT	789,384	1 (ATCT)	2,163
Chicago Midway	316,041	34 (ATCT)	866
Chicago Palwaukee	250,101	53 (ATCT)	685
Chicago DuPage	217,515	74 (ATCT)	596
Aurora	140,567	179 (ATCT)	385

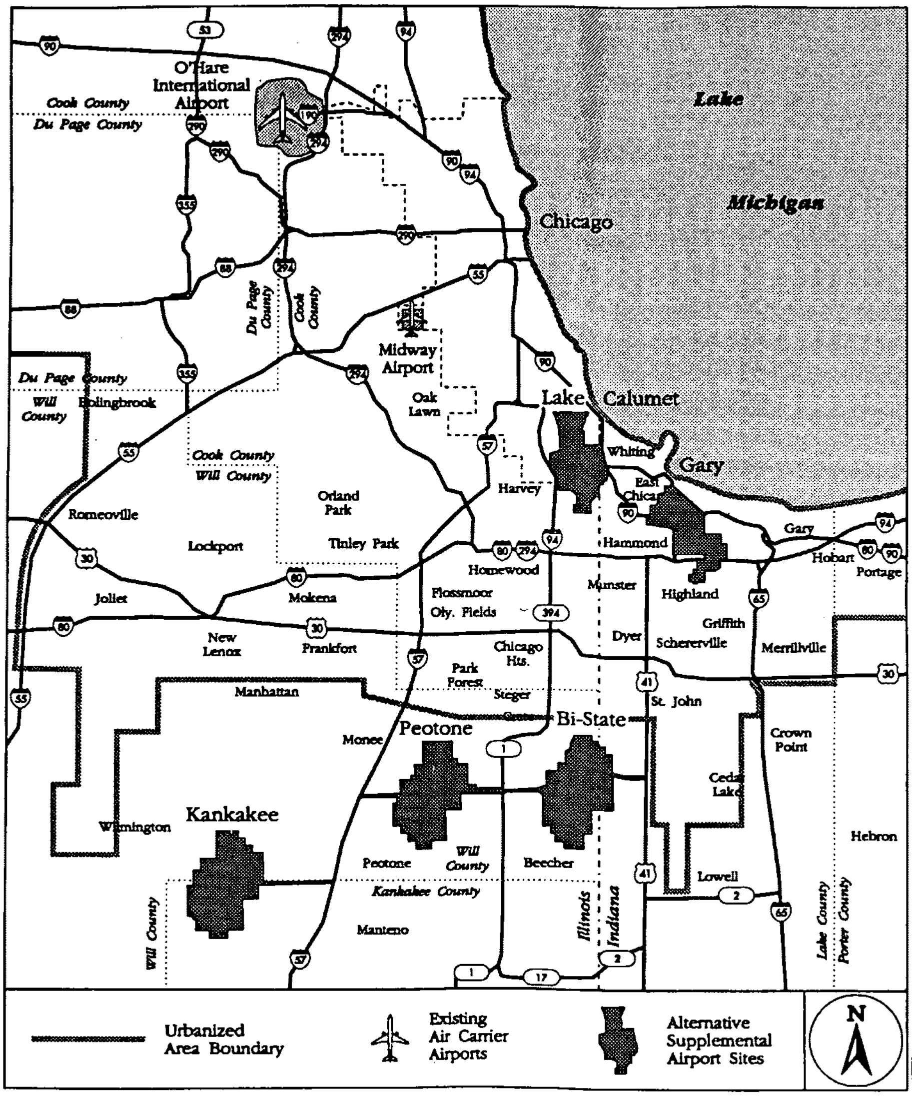

FIGURE 1 Chicago region airports (5).

agement restrictions applied by either the departure or arrival ATC facilities. It is conceivable that full integration of regional airspace and resolution of conflicts may extend beyond the 150 NM range, but given the scope of the study, the study team, in consultation with FAA ATC personnel, determined the 150 NM range to be a reasonable assumption. Because of Chicago's pivotal role, whatever happens in the Chicago airspace affects NAS.

METHODOLOGY

Analysis of Chicago airspace within the site selection framework requires, as a first stage, establishment of a realistic baseline on which the whole airspace design is based. Developing the baseline simulation involves definition of air routes within predefined sectors, existence of air traffic procedures used in Chicago ATC, and determination of the air traffic loading and aviation activities in a representative period. This entailed the following:

- Study and review the airspace and air traffic environment applicable to activity during the baseline period (late 1989 and early 1990) within a certain range that would represent Chicago airspace,
- Evaluate air traffic operations at the Chicago area airports, which includes site observation and data collection at certain airports,
- Verify and validate data collected from various sources, and
- Develop the baseline simulation.

To accommodate an additional major regional airport for the Chicago area, various scenarios are simulated. Scenarios by site, year, and other assumptions considered in the analysis are simulated and include

• Considering planned enhancements for the Chicago airspace in consultation with FAA;

• Applying future regional aviation demand, forecasted in a separate process, to the established baseline and enhanced airspace; and

• Evaluating simulation and interpreting results for various scenarios (alternative sites and demand forecast).

Baseline Data Collection

To establish a realistic baseline for a third major airport in the Chicago area, considerable data is acquired, studied, and reviewed. Documentation studied includes FAA Facility Directives and Letters of Agreement; published flight procedures; terminal and en route sectorization; various related charts, including controller, Coast and Geodetic, terminal control area (TCA), en route high or low airway, and sectional and area navigation charts; a terminal and en route flight progress strip survey; and alternative sites location and layout plans. The most pertinent data collected include Standard Terminal Arrival Procedures; Standard Instrument Departures (SIDs); Instrument Approach Procedures for Chicago airports (O'Hare, Midway, and other selected airports); U.S. Standard for Terminal Instrument Procedures; FAA Great Lakes Region Air Traffic Division Letters of Agreement, directives, and operational manuals; and current arrival or departure route use and volume. Data collection is augmented by visits to ATC facilities and contacting individuals involved in this effort to observe air traffic in progress, collect or verify data on traffic flows, or both, and to document the altitudes of actual arrival and departure aircraft at navigational fixes and along the routes serving the Chicago region.

Flight progress strips, which are used in the ATC system to augment the automatically displayed data as the controllers' tool to manually keep track of flights and their progress, are collected for 7 days (November 5–11, 1989). A total of about 80,000 flight strips is compiled from the Chicago ARTCC and the Chicago O'Hare TRACON facilities. These strips are sorted into arrival, departure, and over-flight categories and become the baseline for the study and airspace model development. One representative day is selected and a detailed analysis of these strips conducted.Computer files from the Official Airlines Guide (OAG) (*6*), which are also used to augment the data collected during the early phases of the inventory preparation process, cover the same period of time as the flight progress strips used. OAG data are entered into the SIMMOD event file to provide airline flight schedules and to verify the data input from the flight progress strips.

The input data base required to develop the basic airspace structure includes location and configuration of existing and proposed airports and airport runways; existing and planned arrival, departure, and over-flight tracks; airways and jet routes within the Chicago ARTCC airspace; and traffic volumes for the study target years for all airports and tower en route operations. Moreover, the FAA NAS Plan (*7*) is scrutinized to examine system improvements planned on a national and regional basis that might affect the Chicago area.

To validate the data, the SIMMOD postprocessor animation capability is used to compare the model logic with real-world air traffic control observed data vis-à-vis airspace issues. Simulation input and logic are adjusted to incorporate controller-type decisions into how the traffic would flow within the airspace system and to and from airports.

Regional Airspace Organization

The U.S. ATC system consists of 23 air route traffic control centers, some 400 airport control towers, more than 200 flight service stations, and more than 1,500 navigational aids (*6*). In the Chicago region, the structure of the airspace system includes the following elements:

• ARTCC airspace: The Chicago-designated ARTCC airspace is described as an area approximately 400 × 300 mi, (120,000 mi²) (Chicago ARTCC data are based on information from FAA Facility Directives, Letters of Agreement, published flight procedures, documentation on terminal and en route sectorization, and other sources) that is divided into 44 sectors: 26 low altitude sectors with nominal jurisdiction from ground level to 23,000 ft mean sea level (MSL), 11 high altitude sectors controlling air traffic from 24,000 to 33,000 ft MSL, and 7 super-high altitude sectors controlling air traffic above 34,000 ft MSL.

• TRACON: Similar to the ARTCC, terminal ATC facilities control air traffic operations within a defined airspace around one or more airports. Generally, the approach control area is a 30 or 40 mi radius of the radar serving the primary airport up to 10,000 ft MSL from ground. O'Hare TRACON designated airspace includes an area approximately 35 × 40 mi (1,400 mi²) and is divided into 13 areas of control: 4 for arrival control, 4 for departure control, and 5 for satellite airport operations. The Chicago terminal airspace extends to 13,000 ft MSL, and within this airspace control zones with more stringent operational and weather criteria enhance safety and facilitate the movement of air traffic within the terminal airspace (e.g., TCA and airport radar service area).

• Milwaukee over-flights: Milwaukee flights to or from the south normally overfly the Chicago terminal airspace at or above 15,000 ft MSL and do not directly contribute to O'Hare TRACON operational considerations or workload. Milwaukee air carrier operations rarely exceed 25/hr and only a portion of these arrive or depart to or from the south over Chicago terminal airspace. These flights are generally segregated from the Chicago terminal operations, but they affect the Chicago ARTCC sector workload in specific areas.

• Satellite airports in the Chicago region: There are several reliever and general aviation airports in the Chicago area, referred to in this study as satellite airports. Operations for the activity generated by those airports in the existing Chicago O'Hare terminal area, mainly general aviation traffic, are included in the airspace model for the target years. The location of these airports, the arrival and departure routes used to serve each satellite airport, and the interaction with both O'Hare and Midway traffic flows need to be accurately determined. However, no unusual flow restrictions were placed in the simulation on flights to or from the satellite facilities and sectors.

Airspace Use

The use of the Chicago airspace by all categories of aircraft and the forecasts of aircraft activity to the target years are as follows:

- Air carrier operations at the primary airports: Aircraft operation at each of the alternative sites for the target years is forecasted separately (*8*). For O'Hare and Midway airports, future aircraft operations for the target years are considered to be their predicted capacity. These forecasted activity levels are the basis for the future flight schedules, or the events file, used in the SIMMOD simulation runs. The arrival and departure tracks for air carrier traffic using the primary airports are defined using radar tapes and other information provided by the FAA ATC. To facilitate the handling of 1,179,889 IFR operations in 1989 in the Chicago terminal area, Chicago ARTCC and O'Hare TRACON used four navigational fixes, or posts. This arrival concept feeds arriving aircraft into orderly, expeditious flows to the landing runways at the destination airport. These fixes are oriented to the northeast, southeast, southwest, and northwest of O'Hare. Jet aircraft are spaced and sequenced at altitudes above the slower air taxi and general aviation turboprop and propeller aircraft. Air carriers departing from O'Hare are routed out of the terminal area between the arrival fixes, and flights departing from Midway are initially restricted to lower altitudes (often 4,000 to 5,000 ft MSL) to separate them from O'Hare arrivals and departures before climbing and being integrated into the O'Hare departure flow.
- Noncommercial operation: This category of demand, which includes general aviation and military traffic, constitutes about 5 percent of the baseline 1989 at the primary airports. Dependent on proximity to O'Hare and Midway, purpose of flight, desired direction of flight, and weather conditions, a large proportion of general aviation flights comes within the sphere of influence created by O'Hare and Midway operations. Interaction of general aviation with a large air carrier airport located at any of the five alternative sites in the metropolitan area would also be expected, especially for aircraft operating to and from an airport within 30 mi of a new airport or those overflying the same area. Figure 2 shows the location of all airports within a 30-mi radius from each of the five alternative sites.

SIMULATION

SIMMOD-generated data from simulation runs representing various scenarios, which investigate variations in the operational performance of the regional airspace system at different situations for the proposed site of the new Chicago Regional Supplemental Airport, are used. SIMMOD is input data-intensive. Required data bases encompass airspace structure, flow and use, airports airfield data, flight schedules (grouping of hubbing activities into flight banks), aircraft characteristics, and lists of events that drive the simulation (*9*). Typically, SIMMOD simulation is conducted in three steps

1. Preprocessing: The simulation first creates the network as defined by the user in the airfield and airspace segments of the input. Data acquisition and compilation are normally integrated in several data files used for the SIMMOD preprocessor element. In this study, the standard arrival and departure procedures and routes developed for each of the alternative sites, the forecasted air traffic for the existing airports in the Chicago area airports, and the five new alternative sites were preprocessed into SIMMOD scenarios.
2. Simulation: The SIMMOD events file, generated either internally within SIMMOD or imported from another data base (e.g., OAG), is used to "drive" the simulation and initiate the aircraft traffic arrivals and departures, both in the air and on the ground.
3. Postprocessing: On the basis of an internal simulation timing routine, the simulation module creates an extensive transaction file representing the progress of the model through time, executing events according to their scheduled time. The postprocessor module uses the simulated events records and other data to generate reports and graphic displays. The postprocessor module can perform several functions, including debugging, validation, formatting, statistical reporting, report generation (tabular and graphic), and graphic animation display (*10*). In terms of air versus ground, route, and node delays, the reporting provides comprehensive data logging and statistical analyses on fuelburn, aircraft operations (takeoffs, landings, and taxiing), and delay. This information can be reported by airline, airspace sector, arrival and departure, airport (or component), type of aircraft and so forth.

The Chicago airspace simulation analysis follows FAA guidelines for the development and generation and interpretation of data for SIMMOD applications (*11*). The SIMMOD reporting system provides extensive and detailed information on various aspects of the system. It is imperative to focus on the type of output data that can provide best coverage of system operational performance measures and avoid unnecessary assimilation of vast amounts of data typically generated.

The following scenarios are used for the development of the Chicago airspace simulation, which included multiple runs identified by case, year, configuration, and other pertinent information.

- Year 1989, 2010, and 2020 baseline simulations included the existing O'Hare, Midway, and satellite airports, which established the baseline for validation and comparison of simulation data resulting from later runs, including the proposed supplemental airport sites.
- Year 2010 simulation runs included the five alternative sites scenarios (Bi-State, Gary, Lake Calumet, Kankakee, and Peotone—each with four runways) and Chicago O'Hare, Midway, and satellite airports, at the 2010 demand forecast levels.
- Year 2020 simulation runs for the scenarios represented each of the five alternative sites (with five runways) and include Chicago O'Hare, Midway, and satellite airports at the operational levels forecasted for 2020.
- Year 2010 scenarios simulated special cases required for various interactive situations involving the Lake Calumet site with Midway airport and the existing Gary Regional Airport. These scenarios include O'Hare, Midway, and the Lake Calumet site, where Midway is considered open, closed, and then

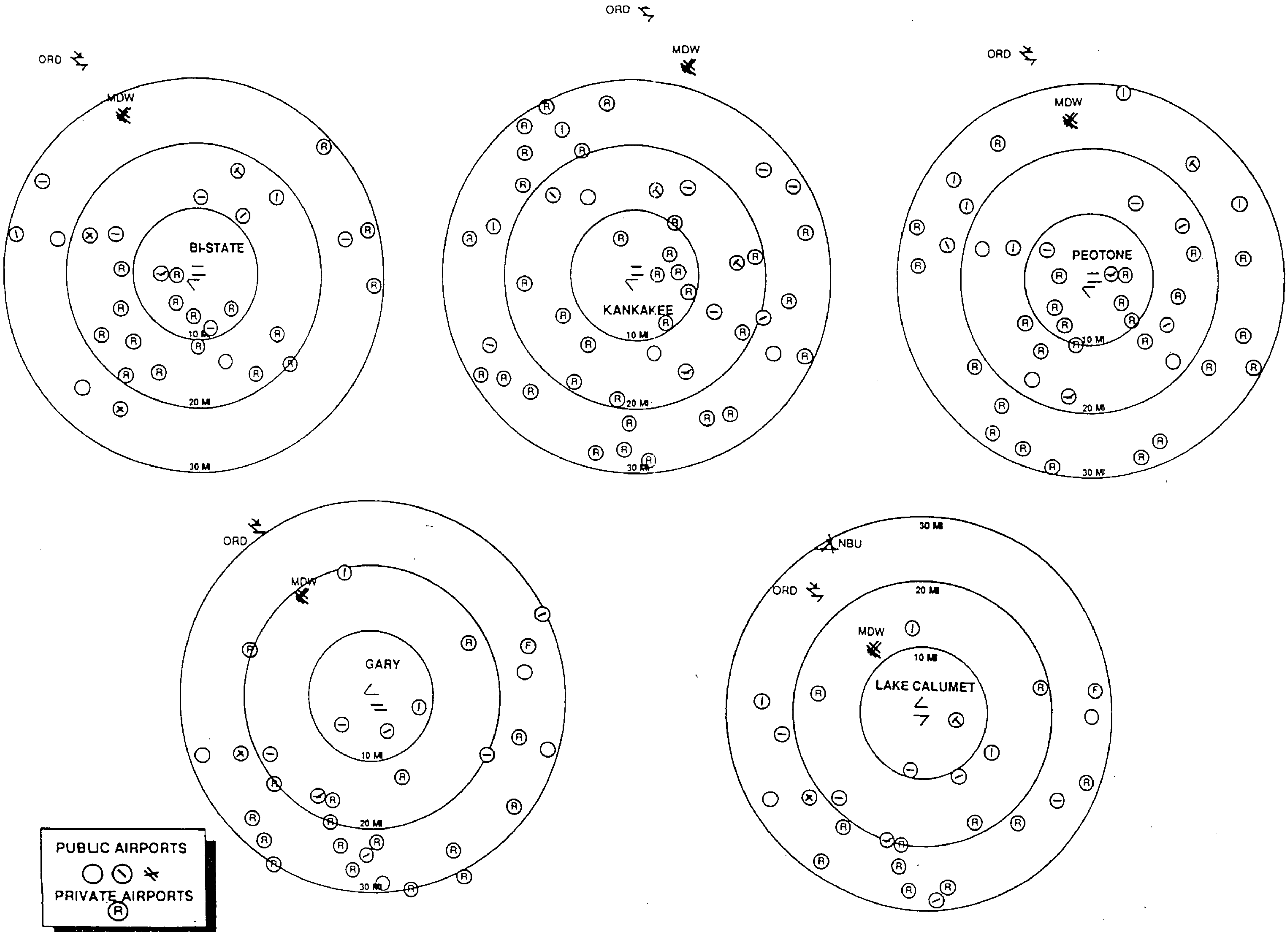

FIGURE 2 Public and private airports within 30 mi of sites (5).

restricted to noncommercial operations only, and the existing Gary Regional Airport's traffic included in the satellite airports operations.

- Year 2020 simulation runs included O'Hare, the existing Gary Regional Airport, and the Lake Calumet site with Midway closed.
- Simulation runs and alternative routes that would mitigate some of the delays predicted by the initial SIMMOD results were included.

Event Data File Development

To establish the data baseline for the SIMMOD Event File, FAA Great Lakes Region Air Traffic Division data are used. Event data for the representative day are independently developed for the airspace simulation model for some specific categories of flight operation. These categories are satellite airport general aviation traffic data, Midway general aviation arrivals and departures, and Milwaukee over-flights. General aviation event data (flights) based on the projection of the 1989 activity levels are added to the events file of the alternative sites. The resulting SIMMOD event file for representative day flight schedule is compared with the actual workload. For O'Hare, the SIMMOD schedule consists of 2,285 flights (2,202 air carrier and 83 noncommercial) compared with the recorded 2,234 flights. For Midway, the SIMMOD schedule consists of 854 flights (665 air carriers and 189 noncommercial) compared with 852 flights recorded on the representative day. For the satellite airports, the SIMMOD schedule includes 540 noncommercial flights with an actual figure of 462.

Total annual operations for the individual airports, including the proposed Chicago supplemental airport, are developed in a separate process (*8*). Conversion factors are then used to convert between representative day activity and annual operations volume. Traffic projections for O'Hare and Midway airports are considered to reflect those facilities reaching capacity by 2010. All traffic growth and delay measurement are compared with the 1989 baseline. For the Lake Calumet site, comparisons are made of the scenarios involving the closing or restricted activity of Midway airport, because the two airports are close. In these cases, the comparisons are made with an average 2010 forecast for the five alternative sites of 530,756 operations. Aircraft groups included in the SIMMOD event file, which is based on FAA categories, are general aviation aircraft (6 models), small (24 models), large (32 models), and heavy (19 models). These include general aviation, commercial air carriers (freighters), and military.

Airspace Network Development

In the development of the airspace network representation for SIMMOD, the regional airspace structure as discussed earlier is used with some modifications.

- Primary jet arrival and departure airspace: Routes within the primary jet arrival and departure airspace (surface to model limit) are included in the SIMMOD airspace network representation on the basis of existing and planned ATC procedures data obtained from FAA during the inventory and data base collection phase.
- En Route low-altitude airspace structure: A separate route structure in the airspace simulation is required for general aviation, air taxi, and other flights using the ARTCC en route low-altitude airway system not included in the tower en route structure. These are flights that are generally handled within the ARTCC low-altitude structure (below 23,000 ft MSL) to and from the Chicago area. Independent routes are established in the model to represent this category of operation.
- Low-altitude tower en route airspace: In situations in which designated terminal airspaces abut, low-altitude en route flights are handled by the terminal air traffic controllers. In the Chicago region, these routes are below 7,000 ft MSL between South Bend, Indiana, Milwaukee, Wisconsin, Rockford, Illinois, and the Chicago O'Hare and Midway terminal area facilities. Although these low level procedures are generally segregated from the majority of the en route air carrier operations, tower en route arrivals and departures must be sequenced with other operations. Independent routes are established in the model to represent this category of operation.
- High-altitude routes: Routes at the high-altitude airspace structure above 24,000 ft MSL are included in the model. Limited over-flight event data are included on these tracks because the interface of this traffic with the Chicago traffic generally occurs beyond 150 NM.
- Over-flights: The volume of Milwaukee over-flights (15,000 ft and above) incorporated into the airspace simulation model is established using the 1989 FAA facility management records for Milwaukee General Mitchell Field along with the city-pair and route use data for O'Hare and Midway.
- General aviation arrivals and departures: Routes are established in the airspace simulation to represent the satellite airports arrival and departure route structure. Flights landing at O'Hare and Midway are integrated with the appropriate traffic flows at the arrival fix and sequenced for the appropriate runways with other traffic, and those destined for satellite airports are segregated on independent routes within south or north satellite sectors of the Chicago terminal area, or both. Departure flights from the satellites are integrated into the existing departure tracks at one of three altitude levels. Departure routes are assigned on the basis of aircraft type, destination airport from 16 city-pair sectors, and existing ATC procedures.

The SIMMOD airspace network structure for the 1989 baseline consists of 290 airspace nodes, 320 airspace links, 240 airspace routes, 44 regional airspace sectors, 16 national airspace sectors, and 11 procedures and plans for airspace only. Composition of SIMMOD model input structure is described in the SIMMOD User Manual (*10*).

ATC Procedures and Confliction Assumptions

As mentioned earlier, input data used in the SIMMOD Chicago airspace simulation are verified and the model is validated by comparing the model logic with real-world ATC and airspace data. Airspace model animation is used to make adjustments required for the validation process. Major assumptions considered in simulation include the following:

• Baseline and forecast arrival and departure procedures: Data from FAA records, flight progress strip survey, existing and planned ATC procedures, inventory, and observations are used to derive the airspace simulation operational events. Details on the operational activity levels are described in the section on Event Data File Development. Sector and route directional loading data (by volume and percent of total) for the airspace in the baseline event file for the Chicago terminal airspace simulation are shown in Figure 3.

• Modeling of O'Hare TRACON: Initial airspace simulation development plans did not call for extensive modeling of the O'Hare TRACON terminal airspace activity. However, the proximity of the Lake Calumet site to Midway made it necessary to conduct modeling of the air traffic activity within the Chicago terminal airspace. It is clear that the interaction between air traffic operations at Midway and Lake Calumet will be significant, especially for the Lake Calumet site. Assumptions included in the simulation reflect the interdependence of arrival and departure flights between the two airports.

• Weather and meteorological conditions: Because the study objective is to conduct comparative analyses for site selection purposes, a representative day weather condition, not weather extremities and capacity variations, is considered in the simulation. The SIMMOD Windset used is based on a complete wind analysis conducted as part of the study (*5*).

• Runway configurations and traffic patterns for the individual alternative sites: For 2010, each of the proposed sites is planned with two sets of parallel runways meeting the current minimum runway centerline separation criteria for simultaneous instrument approaches, a third parallel runway meeting anticipated reduced runway separation distance criteria, and a fourth parallel east-west runway (*5*). For 2020, a fifth runway is added at the proposed airport sites.

• Obstruction analysis: A preliminary obstruction analysis of each of the areas encompassing the five alternative sites is conducted to support the SIMMOD airspace simulation. This analysis, conducted in accordance with FAA PART-77, evaluates the sites for known obstructions above 200 ft. The results are used in developing the instrument procedures for the site's airspace design.

• IFR procedures potential conflictions: For each site, existing instrument procedures are evaluated in relation to potential conflictions that might require special attention.

• Instrument approaches: Sample instrument approaches are developed for each of the five sites. Aircraft are provided simulated radar vectors from the arrival fixes via the SIMMOD airspace network, separated from other traffic, and sequenced to the instrument approach procedure pattern for landing on the appropriate runway.

• Departures and SIDs: Radar SID procedures are developed for each site.

RESULTS

The simulation runs are used to investigate the various scenarios related to the structure and operational aspects of the regional airspace system. These scenarios include the baseline (1989), No-Build (Baseline 2010), and the five proposed sites

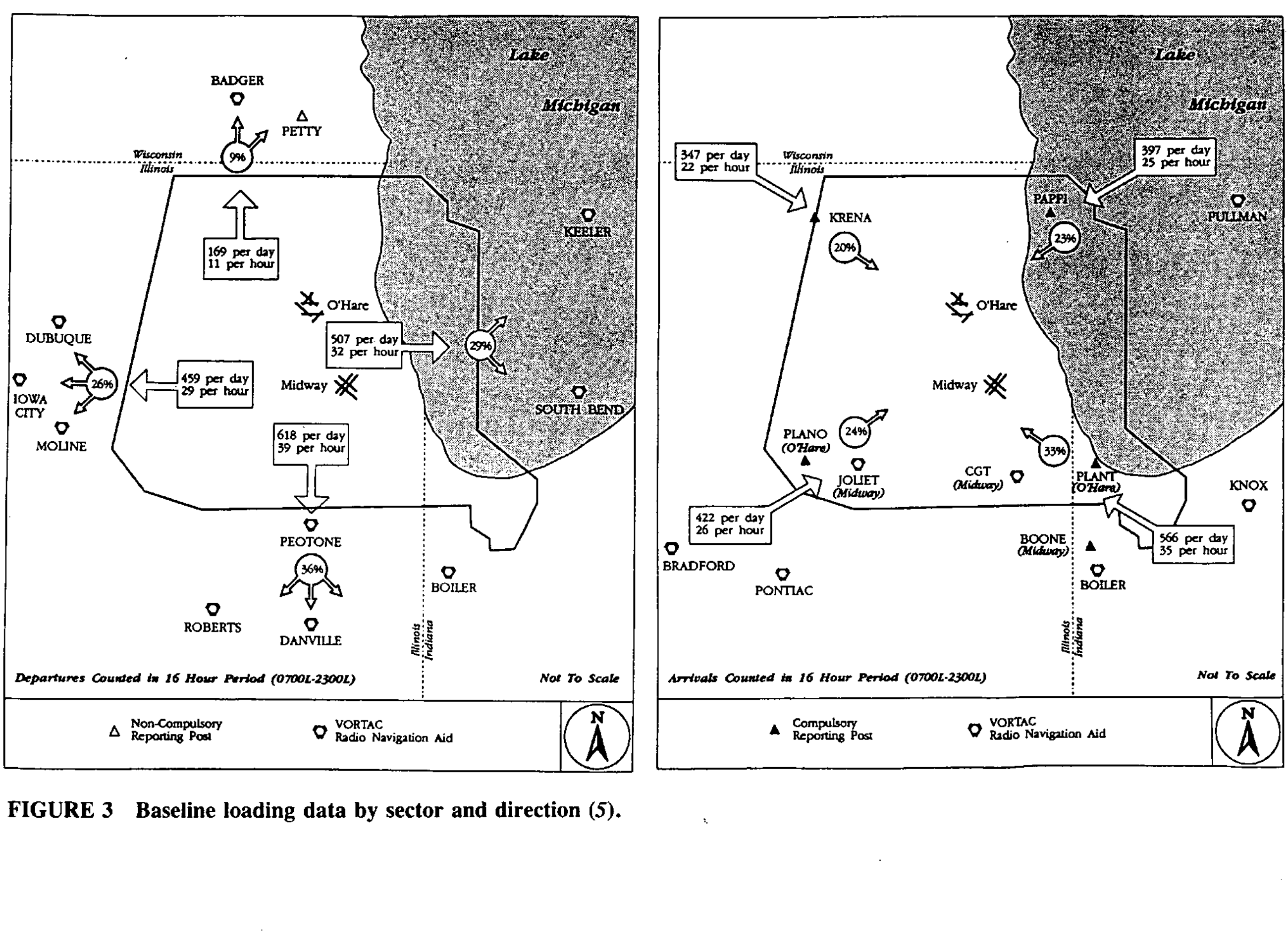

FIGURE 3 Baseline loading data by sector and direction (*5*).

for Chicago supplemental airport. The data base from these simulation runs is analyzed and comparison of statistics discussed. The results are shown in Figure 4.

Baseline (O'Hare and Midway)

On the basis of the assumption that there will be no expansion at O'Hare or supplemental airports, simulation results indicate a 22 percent increase in annual delays for 2010 and 2020. This level of delay is associated with the forecasted increase in operations for the no-build option. Operations forecasted for the baseline airports are shown to grow at about 8 percent at O'Hare and 11 percent at Midway for 2010, a level maintained for 2020. This level of system activity represents approximately 1,164,000 operations compared with 1,068,000 in the base year 1989. Note that the baseline 2010 projections are supply driven and constrained only by the actual capacities of the primary airports. These projections represent only a modest growth in regional traffic from 1990 to 2010, which is not in line with the demand-driven forecasts of aviation activities in the region (passengers and aircraft operations) determined for the five proposed sites in a separate process (*8*). On the basis of this restricted growth (i.e., the no-build scenario), simulation results for average system delay at O'Hare and Midway per aircraft is 10 min in 2010 compared with 9 min in 1990. For O'Hare, average delay per aircraft for the 2010/2020 baseline is 10 min for arrivals and 15 min for departures.

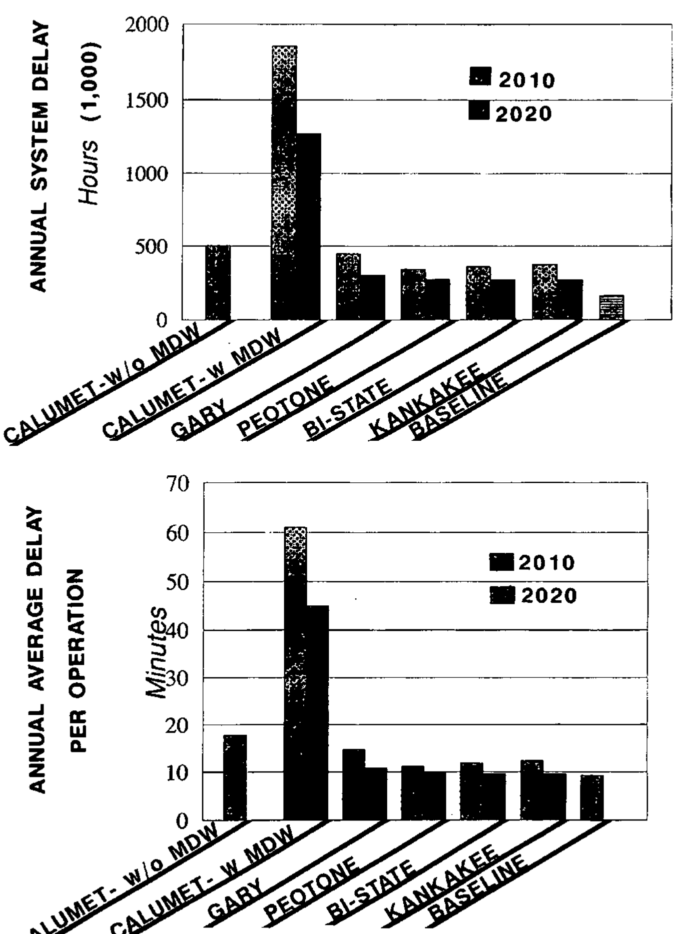

FIGURE 4 Annual delay for baseline and scenarios: *top*, system delay; *bottom*, average delay per operation.

Scenarios for Supplemental Airport Site

Direct comparison between results of baseline airports with and without the supplemental airport may not be meaningful, because the no-build scenario incorporates only a modest, supply-driven growth in regional aviation activity. The activity is constrained by the physical capacities of airports, not what aviation could possibly reach in a demand-driven environment. With a supplemental airport included, system demand will increase to approximately 1,700,000 operations by 2010 (with supplemental airport average of 530,000), and the system delay would also increase considerably. By 2020, the supplemental airport is forecasted to reach 665,000 annual operations, which would result in more significant increases in delay on the system level. Because of increased levels of interaction between operations in the region, delays at O'Hare are projected to increase by 66 percent, with extensive delays at the Midway and Lake Calumet sites. With Midway airport operating, the interactions between its operations and both Lake Calumet and Gary (the urban sites) are significant. Because the complications for Lake Calumet are severe, a scenario is run to model the system with Lake Calumet site, with Midway closed or restricted in operation. Results indicate that for the two urban sites changes in en route or terminal air traffic procedures will not create more airspace or resolve all the interaction and coordination problems. Airspace is limited and finite, and the close-in interactions of the three airports will continue to be a major problem within the terminal airspace. The interactions between Midway and the two urban sites will significantly increase delay for all primary airports.

The system performance results for each of the five proposed sites are as follows:

- Lake Calumet: Several major restrictions of the regional airspace that includes Lake Calumet and Midway are likely to preclude efficient operation of these two airports in one regional airspace structure for the aviation activity levels projected to 2010 and 2020. On the other hand, aircraft operations forecasted for Lake Calumet with Midway closed or restricted is 700,000 in 2010 and 849,000 in 2020—a figure equivalent to O'Hare's 2010/2020 operational levels. The two scenarios of Lake Calumet with Midway closed and Midway restricted to noncommercial operations clearly indicate (a) the volume of aircraft operations forecasted for Lake Calumet with Midway closed will strain the 2020 Lake Calumet airport capacity and (b) restricting Midway to noncommercial operations still results in serious interaction or conflicts between the two airports with significant levels of delays. Moreover, even with Midway closed, the existing Gary Regional Airport represents a potential problem for the Lake Calumet site. The situation might require Gary Regional to be closed or its operations severely restricted. Therefore, the development of Lake Calumet appears to create a dilemma: if Midway remains open there will be extremely difficult airspace and ATC problems and severe delays. If Midway is closed or restricted to noncommercial operations, the demand forecast with continuing peaking patterns will cause stress to airport capacity to the extent that delays will be significantly higher than other sites. Consequently, this situation becomes a serious constraint on the future growth of Lake Calumet Airport. As shown in Figure 4, the total system annual delay for Lake Calumet with Midway open is 1,280,000 hr in 2010 (equivalent to average delay per operation of 45 min) reaching 1,850,000 hr by 2020 (61 min average delay per operation). With Midway closed, total system annual delay for the Lake Calumet site is 540,000 hr in 2010 (equivalent to 21 min average delay per operation) and 550,000 hr in 2020 (20 min average delay per operation). Three issues are noteworthy. First, in terms of total aircraft operations handled by the system in the context of system performance, closing Midway and relocating its equivalent demand to Lake Calumet will have an entirely different effect on airspace than with Midway open and retaining its demand. Second, the 2020 scenarios include improvements to ATC procedures that will result in increased efficiency of the system. Third, to accommodate the increased long-term demand, an additional runway is used for the 2020 scenarios.

• Gary site: Although anticipated delays associated with the Gary site were slightly higher than those for the Greenfield sites, two factors need to be considered: (a) proximity of Gary to Midway and its departure and arrival tracks would not provide more space for development of new procedures, especially south of the airport, and (b) the altitudes available within the system will be limited and competition for the airspace will therefore be severe. It can be concluded from the simulation results that full potential system capacity will not be achieved under the conditions expected to exist if Gary is developed with Midway fully operational; however, no consideration is given to the Midway-closed scenario for the Gary site. Simulation results show that the total system annual delay for the Gary site, as shown in Figure 4, is 300,000 hr in 2010 (equivalent to 11 min average delay per operation) and 460,000 hr in 2020 (15 min average delay per operation).

• Greenfield sites: The three Greenfield sites (BiState, Kankakee, and Peotone), grouped geographically because of similarity of airspace issues, are located approximately 30 to 35 mi south of Midway. Despite the distance, these three sites are not totally free of airspace and ATC interactions, but they are not as severely or critically affected as are the two urban sites. The most difficult airspace issue for these sites is access to the existing east-west departure tracks, where altitude separation will be required for considerable distances to position departing aircraft onto these tracks. Access to the north tracks is somewhat problematic for departures, and these operations are likely to either be delayed, rerouted, or restricted at low altitudes for extended distances. Simulation results indicate (see Figure 4) that total system annual delay for the Greenfield sites (BiState, Peotone, and Kankakee) is lower than the two urban sites, around 275,000 hr in 2010 (equivalent average delay per operation ranging from 9.6 to 9.8 min) and 350,000 hr in 2020 (average delay per operation ranging from 11.2 to 12.4 min).

SUMMARY

The Chicago airspace system analysis conducted as part of the Illinois-Indiana (Chicago) Regional Airport study—Phase I: Site Selection is described. This analysis provides the technical information to assist in selecting one of five alternative sites south of Chicago. SIMMOD simulation is used to generate data on performance measures, mainly delay, to enable the evaluation of different scenarios established for the proposed sites on the basis of a scenario development plan devised to conduct this comparative airspace analysis. Results obtained from interpreting simulation output indicates that there are serious airspace conflict problems and excessive system delay levels for the two urban sites at Lake Calumet, Chicago, and at Gary, Indiana. Airspace restrictions and delays are considerably lower at the three Greenfield sites (BiState, Peotone, and Kankakee) further south.

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Integrated Approach to Statewide Airport Management in the Commonwealth of Virginia

MARGARET BROTEN AND STEVEN MCNEELY

To maintain a safe and efficient air transportation system, Virginia has implemented several management programs to enable the Department of Aviation to monitor and correct existing deficiencies and maximize the benefits received from limited budgets. The three systems discussed in this paper are (a) runway approach identification, (b) airport information management, and (c) pavement management. The runway approach identification system is used to identify obstructions to the approach surfaces for all hard surfaced public-use runways in Virginia. By using the photographs produced through this procedure obstructions are easily identified. The airport information management system is used to store information on an airport's property holdings, approach slope analysis, FAA Form 5010-1, runway and apron pavement data, grant tracking for planning and construction projects, and other valuable data used in airport management and planning. The pavement management system (PMS) is used to store and analyze pavement condition data. PMS provides a coordinated, budgeted, and systematic approach to programming maintenance and rehabilitation work.

All three systems have been of enormous assistance to the Department of Aviation by identifying, quantifying, and storing a large amount of information for quick and easy update and retrieval. The systems have been computerized to allow for ease and speed of the system. The integration of these management systems permits the Department of Aviation to consider all pertinent factors (pavement condition, runway obstructions, and property ownership within runway protection zones) when making decisions pertaining to Virginia's air transportation system.

Since 1928, the Commonwealth of Virginia has taken an active role in the development of an efficient air transportation system. When Virginia enacted its first law in 1928, the Commonwealth had 1 licensed aircraft, 8 airports, and 37 licensed pilots. In the following 64 years, aviation became an important part of Virginia's economic strength.

Virginia's air transportation system consists of 75 public-use airports and 1 heliport, shown in Figure 1. These airports link Virginia with commercial markets, serve as gateways for tourism, generate $1.3 billion in wages, and contribute $6.4 billion to the economic activity of Virginia (*1*).

Before implementing the three management systems, the Department of Aviation relied heavily on the sponsor's knowledge of aviation laws and regulations and their project justification when funding was requested. In most cases, the sponsors consist of some form of a commission or authority in which the members have been appointed by their respective governing bodies. These members may or may not be aviation oriented or familiar with aviation law, regulations, or the real needs of their facility. This lack of experience created problems. In some cases, projects that could have been delayed were funded. In other situations, sponsors should have requested funding for projects but were unaware of the conditions at their airport requiring correction. Safety violations were unrecognized and uncorrected. Paving projects were constructed too soon or too late. Questions of property ownership were raised. Was sufficient land owned for the project being requested? The Department of Aviation and the sponsors had no easy way to review pertinent documents when evaluating safety and capital improvement projects. The Department of Aviation did not have easy access to the necessary information without going through file after file of previous project documents.

As a result of a commitment and responsibility to maintain a safe and efficient system of air transportation, Virginia has implemented several management systems to enable the Department of Aviation to efficiently monitor and correct its deficiencies and take advantage of limited budgets. The three systems discussed in this paper are (a) runway approach identification, (b) airport information management, and (c) pavement management. All three systems have been of enormous assistance to the Department of Aviation by identifying, quantifying, and storing a large amount of information for quick and easy update and retrieval. All have been computerized to allow ease and speed of the system.

The runway approach identification system (*2*) is used to identify obstructions to the approach surfaces for all hard surfaced public-use runways in Virginia. By using the photographs produced through this procedure an airport authority can easily identify and remove obstructions. The airport information management system (AIMS) (*2*) is used to store information on an airport's property holdings, approach slope analysis, FAA Form 5010-1, runway and apron pavement data, grant tracking for both planning and construction projects, and other valuable data used in airport management and planning. The pavement management system (PMS) (*3*) is used to store and analyze pavement condition data. The program facilitates the development of annual maintenance plans and long-term (5 to 10 year) capital improvement programs.

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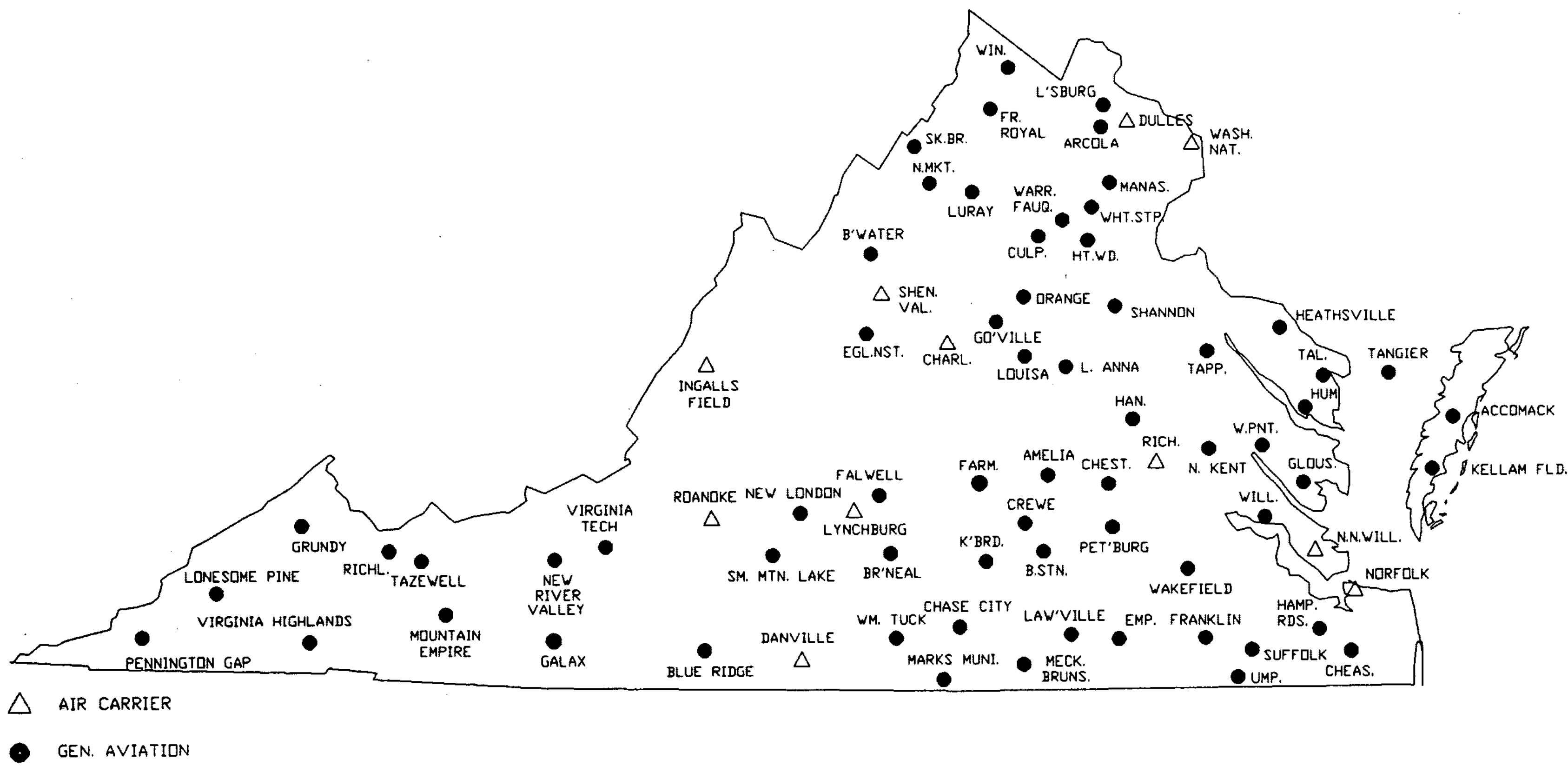

FIGURE 1 **Virginia air transportation system.**

VIRGINIA RUNWAY APPROACH IDENTIFICATION SYSTEM

In 1986 the Virginia Department of Aviation determined that there was an urgent need to identify obstructions to the approach surfaces for all hard-surfaced public-use runways in Virginia. FAA is concerned about the presence of obstructions in runway approach surfaces, as stated in Federal Law (Section 18 of the Airport and Airway Development Act of 1970) (*4*) and FAA Advisory Circular 150/5300-13 (9/29/89) (*5*). Figure 2 draws an obstruction within the approach surface of a runway.

Demonstration Project

In 1986 the Department of Aviation initiated a demonstration project at the Emporia Municipal Airport to investigate the usefulness of a process known as Photoslope in identifying obstructions. Photoslope, developed by G.C.R. & Associates, Inc., is a terrestrial photographic surveying process used to document the condition of a runway end approach surface in accordance with FAR Part 77 and FAA Form 5010 reporting procedures. The method uses a series of photographs to identify visually and mathematically any obstructions to the approach surface.

Photoslope takes traditional obstruction identification surveying methods one step further by attaching a camera to a precision theodolite. The result is a series of ground-level photographs that establish the plane and outside limits of the approach and transitional slopes. These "lines" can then be superimposed on the photos with a high degree of accuracy. The major advantage of Photoslope over traditional surveys is that it provides actual photographs—in correct perspective—as an end product.

Each runway end is evaluated to locate the most severe obstruction, and the approach slope required to clear that obstruction is calculated. The critical obstruction is located (identifying its distance from the runway end or primary surface, its distance left or right of the centerline, and its height and required slope to clear the obstruction) by digitizing the photographs and using triangulation procedures. Figure 3 shows the Photoslope procedure.

During the evaluation period of the sample project, several comparisons were made between traditional obstruction identification surveying methods and the Photoslope method.

- Unless an airport sponsor has a surveying or engineering background, it is often difficult for that person to understand the conventional method of plotted obstructions on a plan and profile view (as used in master plans). Photoslope makes it easy to show and describe the problem to the airport sponsor. If the sponsor then has to approach an adjacent property owner for obstruction removal, it is much easier to show the owner the extent of the removal required.
- By using Photoslope, whether the entire approach surface area was covered during the survey can be ascertained quickly simply by matching the photographs. Under the conventional method, the information is recorded in a field survey book by a surveyor who may have missed an obstruction, and there is no easy way to check the collected information.
- A cost analysis revealed that the difference between Photoslope and the conventional aerial photography was quite substantial (*6*). Photoslope costs approximately $1,700 per runway end; aerial photography costs $2,400 per runway end. The cost of updating the photographs is approximately $100 per runway end.

Statewide Implementation of Photoslope

The results of the demonstration project confirmed that Photoslope provided an excellent way to detect the presence of obstructions within a runway approach surface. Because of the success of the sample project and the favorable comments of the airport authority of the Emporia Municipal Airport, the Department of Aviation decided to continue implementing the Photoslope process at the remaining public-use air-

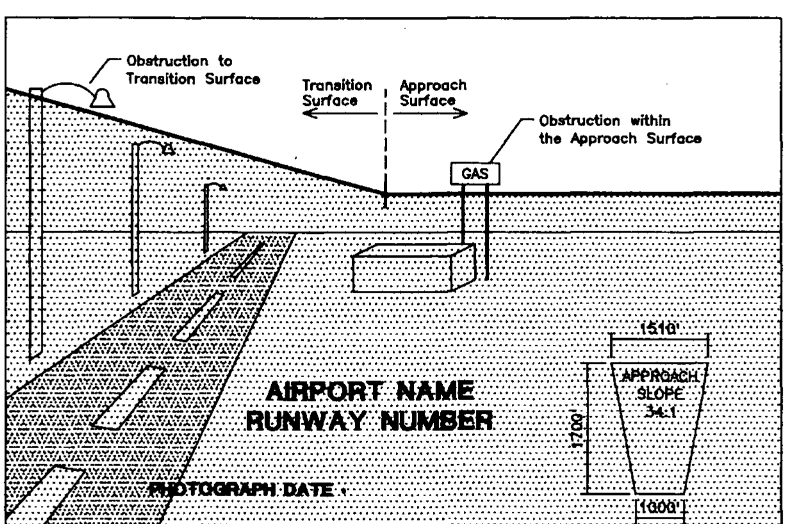

FIGURE 2 Approach surface to a runway with an obstruction.

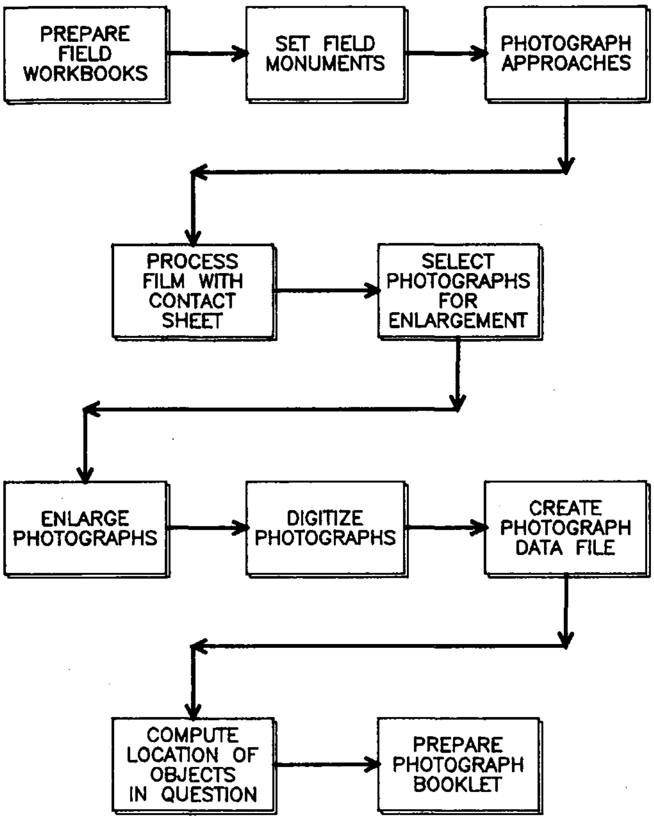

FIGURE 3 Photoslope procedure.

ports in Virginia. The first phase of the project consisted of 28 airports with 78 runway ends. The second and final phase consisted of 36 airports with 80 runway ends.

The steps in the Virginia runway approach identification system are as follows:

1. Verify the runway approach slope and width with FAA and the Virginia Department of Aviation.
2. Survey and establish at least three permanent monuments at each runway end for the airports identified for use of the Photoslope process.
3. Photograph approach surfaces using Photoslope.
4. Organize necessary vertical and horizontal data control to locate and size any violations or penetrations of the approach slopes observed in the photographs.
5. Specifically locate and size the most severe obstructions at each runway and calculate the approach slope required to clear them.
6. Prepare a field-work information sheet for each runway end, describing the exact location of permanent monuments and procedures required to photograph the approach surfaces for the runway end.
7. Prepare three copies of a Photoslope booklet that contains photographs depicting the status of the approach for each runway at the airports identified.

The Photoslope booklets and information sheets for each airport were presented in numbered, coded hanging files ready for placement in a 12-in.-wide drawer filing cabinet. Three sets of the Photoslope filing system were provided. One set for the FAA, one for the airport sponsor, and one for the Virginia Department of Aviation.

Equipment and Training Needs

For future updating of data, the Department of Aviation purchased the following equipment and training.

- One T-16 Wild theodolite with tripod and one P-32 Wild Terrestrial Camera,
- Eight hr of classroom instruction in runway approach and transition surfaces with an introduction to how Photoslope identifies these surfaces,
- Eight hr of classroom and field training in the use of the T-16 theodolite and P-32 Terrestrial Camera, and
- Field training at selected airports.

Summary

The Department of Aviation, with partial funding from FAA, contracted for 158 runway ends at 64 airports. This covered all the public-use hard-surfaced runways. The final product provided the Department of Aviation with LORAN coordinates as well as rectangular coordinates on each runway end and airport reference point. The total contract was more than $330,000 and the department purchased the equipment to update the photographs itself.

Within 1 year of the completion of the Photoslope Systems Plan in Virginia, which showed only two airports in the state to have clear approaches to all runway ends, more than 40 airports were clear of obstructions. This monumental task was accomplished because Virginia adopted and enforced regulations excluding an airport from receiving federal or state funds if there were obstructions to the runway approach surfaces. The program administered by Virginia allows airports to ask for and receive funding for airport improvements if the project contains "obstruction removal" as an item in the grant request.

Photoslope has enabled the Department of Aviation to evaluate, quantify, and correct the conditions of the runway approaches in Virginia. The Department, along with the airport sponsor, has begun clearing or mitigating obstructions to the approach surfaces. The photographs have made the decision of which objects need to be removed much easier for the sponsor. All comments from the sponsors have been favorable. Safety has been improved and will continue to be improved as a result of the Virginia runway approach identification system.

VIRGINIA AIRPORT INFORMATION MANAGEMENT SYSTEM

In 1987 the Virginia Department of Aviation began a comprehensive inventory and assessment of public-use airports in the state to document approach surfaces and property ownership. This effort was initiated as a statewide aviation systems plan, and the results were intended to comply with FAA safety standards. The Photoslope process was used to document runway approaches and the AIMS program was instituted to establish and verify land ownership.

In 1988 the Virginia Department of Aviation with FAA completed the initial phase of a systems plan program to identify obstructions to runway approaches using Photoslope. While establishing the status of the runway approaches at the subject facilities, it became evident that individual airports and, therefore, the Department of Aviation, lacked sufficient information on the properties owned, leased, or under easement rights. In addition, it was determined that a significant number of the runway approach obstruction problems are caused by insufficient control of the property surrounding the runway.

The AIMS program, developed by G.C.R. & Associates, Inc., was implemented to facilitate the retrieval of property information. It is a completely automated system that provides instant access to airport information. The system is specifically designed to meet the daily needs of individual airport sponsors and the Department of Aviation. The program includes information on an airport's property holdings, approach slope analysis, FAA Form 5010-1, runway and apron pavement data, grant tracking for planning and construction projects, and other valuable data used in airport management and planning. Through use of menu-driven screens, such information is immediately available and suitable for use on demand.

AIMS Components

The purpose of the AIMS program is to provide documentation for the land currently owned by each airport and to compare this with the property interest that should be held to meet the operational requirements of the runways and their designated classifications. The program also establishes a consolidated file of all documents confirming the ownership or control of airport properties in conformance with FAA recommendations. In addition to the hard copy file folder, AIMS includes software that provides access to a data base containing information about the property owned or under the control of the airport and other general and technical information about the airport. AIMS components are as follows:

- Photoslope booklet,
- AIMS summary document,
- Property deeds folder, and
- AIMS software and computer data file.

Photoslope Booklet

The Photoslope booklet is the result of the complete Photoslope process and contains all information necessary to duplicate the process and identify the controlling obstruction to the runway approach surface, and it contains the actual photographs for each runway end at the airport. The copy of the Photoslope booklet retained by the Virginia Department of Aviation has been restructured and is now an exhibit in the AIMS summary document prepared for each airport as a part of this current project. As part of the AIMS computer program, the Photoslope analysis and actual photographs for each runway end are also retained as a computer data file and are accessible for viewing on a VGA color monitor.

AIMS Summary Document

The AIMS summary document is a three-ring binder prepared for each airport. It contains a synopsis of illustrations, summary information on the status of the runway approaches, and real estate files of the airport. An important product provided in the summary document is the property illustration map. This illustration identifies the total land area of the airport and each parcel acquired by the airport to establish the total area.

In addition to the various maps and illustrations of the airport, the Summary Document includes a copy of the Photoslope booklet and a summary of the property deeds folder. The maps and illustrations in this document are intended to assist the reader in visualizing the layout of the airport and provide access to the basic reference maps and drawings depicting the airport. Such information and maps are often used on a daily basis by airport managers, FAA, and Department of Aviation staff.

Property Deeds Folder

The property deeds folder contains copies of the actual source documents confirming the airport's ownership of the land depicted on the property illustration map, which is established as a component of this study. It provides an illustration and a copy of the source documents (if found through the search of the files at the FAA, the Virginia Department of Aviation, or direct communications with the airport management) for individual parcels of land. The folder uses a cross-reference number system to match the source document to the parcel on the property illustration map. A property deeds folder was prepared for each airport and organized to provide an immediate, comprehensive filing system for the Virginia Department of Aviation to help maintain the real estate files. This organization is in accordance with FAA recommendations.

AIMS Software and Computer Data Files

A major component of this project is the AIMS software and data files for each of the airports. The AIMS software is a user friendly menu-driven system that provides the user with access to a wealth of information about each airport in the system. The primary benefit of the AIMS software is that it converts data into information. Through the appropriate organization of data on airport facilities and operations, AIMS provides the user with a convenient and accurate means of obtaining managerial information for routine daily activity. The program software contains the following data.

- General airport information and layout illustration,
- Photoslope analysis and actual photographs,
- Property layout map and real estate files,

- U.S.G.S. quadrangle map,
- Aeronautical chart illustrating each airport,
- FAA Form 5010-1 information, and
- Construction and planning grant information.

In addition to providing access to the information for each airport, the AIMS program summarizes the information for queries at the state level to help the Department of Aviation view statewide statistics.

AIMS Implementation

During the course of this study, a survey was mailed to each airport in the system plan. Although each airport was contacted directly by the consultant and the Department of Aviation, only 35 airports provided source documents or actual deeds confirming ownership of the airport properties. Most real estate information was obtained from FAA or Virginia Department of Aviation files. Through the efforts described it was realized that many airport sponsors did not have the proper documentation to confirm property ownership. As a continuation of this process, the Department of Aviation will strive to acquire all land documents available.

VIRGINIA PAVEMENT MANAGEMENT SYSTEM

In September 1990, the Virginia Department of Aviation approved a contract with ERES Consultants, Inc., assisted by Pavement Consultants, Inc., for the implementation of a comprehensive PMS for airfield pavement evaluation and management. Sixty-one commercial, reliever, and general aviation airports were included in this study. The PMS implemented by the team members initially accessed the computer program Micro PAVER (*7*), developed by the Corps of Engineers, Construction Engineering Research Laboratory, and used supplemental budgeting and prioritization software created by ERES Consultants, Inc. The use of the Micro PAVER system was temporary, however, and was replaced by ERES' PMS software in the final delivery.

The work to meet the project objectives included gathering information pertaining to pavement history, defining the pavement network, conducting visual condition surveys, performing nondestructive deflection testing (NDT) on selected runway pavements, and establishing a PMS data base. Maintenance and repair (M&R) cost estimates and prioritization schemes were integrated into the PMS software, and computerized maps showing network layouts and condition ranges were developed. Individual airport reports were prepared and distributed to airport sponsors, the Department of Aviation, and FAA.

PMS Overview

The four primary activities performed during pavement management are network inventory compilation, data base development, network data analysis, and project-level analysis. A network inventory includes information pertaining to the pavements under an agency's jurisdiction. Once the sectioning has been completed, a data base can be developed as a means of establishing an efficient filing system. Pavement management provides information for decision making at two distinct levels: (a) network level management and (b) project level management. Network level management involves the evaluation of all pavements under the Department of Aviation's jurisdiction to determine M&R needs into the future for the preparation of multiyear budget plans. When a section has been identified as a candidate for repair, it is evaluated at the project level. This analysis level requires detailed inspection sampling rates, often 100 percent. Other testing, such as NDT or coring, provides additional insight into pavement condition and distress mechanisms, which in turn is useful in selecting the proper corrective treatment.

Three pavement management philosophies are often applied today. The most commonly used and least sophisticated management approach involves selecting and applying repair alternatives that are familiar and have worked satisfactorily in the past. Unfortunately, this approach often precludes the consideration of many alternatives that may have, under further analysis, provided the most cost-effective solutions to a pavement problem.

An improvement on the first approach involves the evaluation of existing pavement distresses before the selection of feasible M&R alternatives. This approach allows consideration of all repair techniques that may correct the existing deficiencies and delay their recurrence. However, no consideration is given to the life-cycle cost. This approach may thus eliminate consideration of an alternative with high initial costs but low maintenance costs over its design life.

The preferred approach to pavement management, which the Virginia Department of Aviation selected, uses the results of the in-depth pavement evaluation and the development of representative deterioration models to predict future condition throughout a pavement's life. This pavement condition prediction in turn permits the comparison of various repair alternatives on a life-cycle cost basis over the design life of each alternative, resulting in better decisions on the basis of cost effectiveness.

For the preferred pavement management approach to work, an accurate projection of future pavement condition is required. The objective and repeatable indicator used to identify current condition is the pavement condition index (PCI). This index has been adopted by the FAA as an indicator of existing pavement condition (*8*). By projecting the rate at which the condition will change over time, a meaningful life-cycle cost analysis can be performed to compare the initial costs of various M&R alternatives and identify the future maintenance costs associated with each alternative under consideration. In addition to identifying the most economical repair alternative by condition-prediction modeling, the optimal time for applying treatments can be identified. Typically, the optimal repair time is the point at which a gradual rate of deterioration begins to increase at a much faster rate. It is critical to identify this important point to avoid higher M&R costs caused by excess deterioration.

PMS Implementation

Although the Micro PAVER system is useful in storing and retrieving inventory and condition information, it did not provide the budgeting and planning capabilities the Department of Aviation required. Because of these limited capabilities, the department implemented the ERES' PMS system, which assists in the generation of customized annual and long-range plans.

On the basis of data stored in the data base, interviews with the Department of Aviation engineers, and engineering experience, the team identified the M&R alternatives being used by the airports and the unit costs associated with each of them. Customized deterioration curves were established for similar types of pavements on the basis of results of the PCI field surveys. Following this task, decision trees were constructed to determine the feasibility of each alternative on each type of pavement. Finally, a prioritization scheme was developed with the department to identify the highest priority pavements for the allocation of available funding.

Customized Deterioration Curves for Performance Prediction

One of the first steps was to divide the network into groups of pavements that perform similarly. These groups are termed "families" and were developed to establish deterioration curves reflecting the actual performance of these pavement types (*9*). The families distinguished among asphalt runways, taxiways, aprons, and concrete pavements. The curves were further subdivided by airport type, grouping general aviation and reliever airports together and commercial airports as separate items. Because of a lack of data, all concrete pavements were grouped together to develop one curve. Expert points were added to three family curves to improve their prediction calculation at the point where pavements were 40 years or older.

The data were divided into two geographical regions to determine the impact of climate on deterioration patterns. It was found that the curves were not different enough to warrant separate modeling equations, particularly between pavements 0 to 30 years old. However, as additional performance data are collected, those curves will be examined again.

Repair Alternatives Module

The next step in customizing the software involved determining rehabilitation alternatives to be considered to repair specific distresses. The applicability of applying these rehabilitation types in different situations and repairing different types of pavements was discussed, as were the impacts on the condition and typical costs. The unit costs for each alternative were broken down into two components. The first was initial cost of the repair per square foot and the second was the annual cost following the repair. These costs are used in the life-cycle analysis to determine the life cost of each alternative considered. This step in the customization process ensures that there is a direct applicability of the recommended treatments to the existing techniques used by the department.

Prioritization Module

A prioritization scheme was then developed to assist in ranking pavement rehabilitation alternatives according to the practices used by the Department of Aviation. This technique enables M&R strategies to be performed on pavements in a more critical situation. By using these inputs, the software analyzes each section in the data base to determine whether it is eligible for repair. If so, each decision tree is evaluated to determine which alternatives are feasible for the particular conditions of the section being evaluated.

Budgeting and Planning Software

A benefit/cost ratio is determined for each alternative, and the highest ranking ratio is selected as the recommended treatment for that particular section. Benefit is determined as the area between the section's deterioration curve, assuming no repair is done, and the new deterioration curve for the section, following the repair. Costs are determined on a life-cycle cost basis so that alternatives with differing useful lives can be evaluated on an equal basis. On the basis of the user input budget estimates and the department's prioritization scheme, the ratios are ranked for each year in the budget analysis.

A five-year capital improvement plan can be prepared using the Budget Optimization Program. For each individual airport, or the system as a whole, the budget report identifies feasible rehabilitation alternatives from the list of alternatives entered into the decision trees. The feasible alternatives for each section are evaluated on an automatic life-cycle benefit/cost analysis and then ranked in order from the most beneficial to the least beneficial on the basis of the pavement section's priority among other pavement sections and actual dollars available.

The software budgeting capabilities were customized to make the system useful to the department. The software was adjusted to make it possible to input the different type of airport (general aviation, reliever, or air carrier) so that separate reports could be run for different funding sources.

Maintenance Program

An individual maintenance and repair policy was developed for the Virginia statewide airport data base from direct interviews with the Department of Aviation. Each data base contains the distresses, severity level for each distress, code for the maintenance and repair, and description of the maintenance and repair. The data base also contains the maintenance and repair policies for asphalt concrete and portland cement concrete pavements.

Computer-Aided Drafting Link to Data Base

The final software delivery permitted generated reports to be linked with computer-aided drafting drawings of each airport, allowing all software outputs to be displayed graphically. This capability is unique in its flexibility and ease of use. The generated maps can be displayed on the screen or sent to a plotter or printer for use in presentations and reports. This feature is a powerful management tool, presenting information in a clear, concise, and easily understood format. These reports can be generated in a matter of seconds and provide the type of information needed to justify budget expenditures and M&R alternative selections.

Future Requirements

The usefulness of the information obtained from the PMS depends on the quality of the data being used. To maintain the integrity of the data base, it is the Department of Aviation's responsibility to ensure that the system continues to represent the environment under which it operates. To do this, several modules of the program should be reviewed periodically to keep the data in the system current. The items to be addressed are as follows:

- When pavement deterioration trends have been established, the condition of the pavements should be measured every 3 years;
- The treatment matrices should be reviewed each year to reevaluate treatment types and costs;
- Deterioration curves should be updated whenever new performance data become available;
- Maintenance policies should be reviewed annually to determine whether the maintenance activities and costs are still representative of conditions within Virginia;
- If rehabilitation projects alter the pavement management sections or new sections are added to the network, the system should be modified; and
- Any major M&R performed should be stored in the data base.

PMS Summary

With the completion of this study, the Virginia Department of Aviation has a state-of-the-art PMS in house and operational. It contains an up-to-date data base and is easily operated by the staff. Through this program, the department is able to select specific rehabilitation methods based on engineering and economic considerations. In addition, the program will help the state and FAA prioritize pavement rehabilitation work. Because the system establishes a time frame for rehabilitation work, it will enable the sponsor, state, and FAA to better budget and allocate funds. In addition, it will enable the Department of Aviation to better use its existing maintenance program, which provides funds for extending the life of pavements through routine maintenance. The PMS will provide a coordinated, budgeted, and systematic approach to programming maintenance and rehabilitation work.

INTEGRATION OF THREE AVIATION MANAGEMENT SYSTEMS

The three management systems are used in conjunction to help the Department of Aviation evaluate capital improvement projects for funding. These systems enable the Virginia Department of Aviation, with limited financial resources, to make sound decisions when funding projects while maximizing the use of tax dollars. The computerized systems also allow the department to easily and readily access enormous amounts of valuable information on the 75 public-use airports in Virginia. This quick access of information contributes to the speed at which the staff can respond to a sponsor's need for assistance, which enhances the working relationship.

CONCLUSION

The Virginia Department of Aviation has determined that the three systems discussed in this paper, Photoslope for runway obstruction identification, the AIMS program for property ownership identification, and the ERES PMS software for pavement maintenance and rehabilitation programming, have all proved to be powerful management and planning tools. The integration of these systems allows the Department of Aviation to rapidly consider all pertinent factors (pavement condition, runway obstructions, and property ownership within runway protection zones) when making decisions pertaining to Virginia's air transportation system. The facilitation of the decision-making process is important because the condition of the aviation system directly affects the economy of Virginia.

ACKNOWLEDGMENTS

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Demand for Aircraft Gates

MAZEN I. HASSOUNAH AND GERALD N. STEUART

Demand for aircraft gates, which is defined as the number of aircraft expected to require the service provided at a terminal building at any given time during one day's operation, depends on flights scheduled and their actual behavior relative to those schedules. The schedules provide a deterministic element to the process of generating the actual number of aircraft at gates, and deviation from these schedules provides a stochastic element to the process. A model that incorporates these two elements has been developed to estimate gate requirements at airports. The results of applying the model to an actual operation of aircraft gates have demonstrated the ability of the model to describe gate occupancy as a function of time of day with reasonable accuracy. The results have also shown that a common gate use strategy (i.e., first-come, first-served discipline) requires fewer gates than strategies under which the use of gates is restricted to flights of a particular air carrier or sector. Furthermore, it has been demonstrated, given a scheduling practice involving bank operations, how the time interval between banks influences the requirement for gates.

An air terminal's ability to process aircraft and passengers depends to a large extent on the interface between the terminal building and the aircraft. This interface is carried out at aircraft gates. The term "gate" designates an aircraft parking space adjacent to an air terminal and used for the servicing, loading, and unloading of a single aircraft. A major problem facing operators at many large airports is that demand for gates at certain times of the day often exceeds the number of gates available. Previous work has shown that deviation of flights from their schedules tends to increase the number of aircraft gates required during the busy periods of the day (*1*). The objective of this research is to study demand for aircraft gates given an underlying flights' schedule and the variation in their actual behavior from this schedule. Demand is defined as the number of aircraft expected to require a connection with the terminal building at any time during the operation of 1 day. As part of the analysis it is possible to investigate the influence of different scheduling practices and assignment strategies on gate requirements at airports.

Most procedures used in the past for estimating gate requirements at airports have been based on either average performance figures or idealized stochastic models. Horonjeff and McKelvey (*2*) suggested the following deterministic formula for computing the required number of gates (G):

$$G = (CT)/U \quad (1)$$

where

C = design volume of arrivals or departures (aircraft/ hr),
T = weighted average gate occupancy time (hr), and
U = gate utilization factor.

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The gate utilization factor represents the amount of time the gates are occupied in relation to the time available. This factor must be applied, because it is virtually impossible for all gates available at a terminal building to be used 100 percent of the time. The technique is a valid planning tool if the scheduling practices and aircraft servicing procedures are assumed to be fixed. Precise schedules, however, are rarely available during the planning stages of an air terminal. In addition, flights usually deviate from their schedules, and airport operators have to alter their service practices to cope with these deviations. To recognize the stochastic nature of flight arrivals and departures, Bandara and Wirasinghe (*3*) defined, for planning purposes, the number of gates as

$$G = R(T + S) \quad (2)$$

where R, T, and S are random variables that represent arrival rate, gate occupancy time, and separation time, respectively. The separation time, S, is selected as a substitution for the utilization factor in Equation 1 and defined as the time between departure from a gate and the next arrival. Data from Vancouver International Airport showed that the probability distribution of G during peak periods can be approximated by Type I extreme value distribution.

A queueing model that assumes the arrival of flights to be homogeneous Poisson and gate occupancy times to be exponentially distributed has been proposed by Rallis (*4*). The Poisson process assumes the number of arrivals in nonoverlapping time intervals to be stationary. This is not the case in the arrival process of flights due to the influence of their schedules.

Many computer programs have been developed to simulate the daily assignment of aircraft to gates at airports (*5,6*). In these programs a fixed schedule of flights has been used as an input source to a queueing system in which the service mechanism has been a gate assignment strategy and deviations from the schedule have not been allowed. To overcome this shortcoming, Gosling (*7*) has proposed a gate assignment expert system that, in addition to its ability to deal with gate assignment under normal situations, could be used to assign aircraft to gates under situations in which flight operations depart from a predefined plan. The system has been applied to a small operation of aircraft gates at Denver Stapleton Airport, and the ability of the system to deal with large-scale gate operations is yet to be investigated.

The actual arrival and departure times of flights in relation to their scheduled times, and the effect of this variation on the demand for aircraft gates, were first studied by Steuart, who developed a simple stochastic model based on time-dependent Bernoulli trials to investigate how strategies of scheduling flights influence the demand for aircraft gates (*1*).

His work concentrated on bank operations where all flights in a bank were assumed to have the same behavior. The time dependent Bernoulli parameter $p(t)$ was defined in the model as the probability that a gate is occupied by an aircraft at a given time t, and all the moments of the resulting binomial distribution were determined from this parameter. Empirical data collected at O'Hare Airport, Chicago, were used to estimate the parameter $p(t)$.

The work presented in this paper is an expansion on Steuart's earlier work. The relationship between occupancy of aircraft gates and flights' behavior is established. A stochastic model, based on the assumption that each flight has a unique behavior relative to its scheduled arrival and departure times, is then developed to estimate the demand for gates as a function of time of day. Finally, an application of the model to an actual operation of aircraft gates and procedures to estimate gate requirements under different scheduling practices and assignment strategies are presented. Only operations of aircraft gates on regular days are considered in this study. Operations of gates on irregular days in which bad weather conditions or air traffic control failures, or both, occur were a subject of another study by Steuart (*8*) who showed the schedule to have little or no effect on the process of generating loads on gates on these days.

FLIGHT BEHAVIOR AND OCCUPANCY OF AIRCRAFT GATES

Gate occupancy can be described by arrival and departure times of each flight. As a result, the measure of occupancy performance is taken to be the relationship between a flight's actual arrival and departure times relative to the schedule. The difference between a flight's scheduled arrival time and its actual arrival time is defined as an arrival lateness. A negative arrival lateness implies the flight arrived before its scheduled arrival time. Similarly, the difference between the flight's scheduled departure time and its actual departure time is defined as a departure lateness. Flights usually do not depart before their scheduled departure time, and a negative lateness is not expected. Figure 1 shows a scatter plot of the joint arrival and departure lateness of 750 flights that arrived at Terminal 2 of Toronto's Lester B. Pearson International Airport from October 16 to November 3, 1987. Points within 15 min of arrival lateness demonstrate considerable scatter, which would imply that departure lateness is independent of arrival lateness within this range. As the arrival lateness becomes larger, the points show a correlation between arrival lateness and departure lateness.

Flights may experience departure lateness because of arrival lateness or other factors such as mechanical or security problems. To distinguish between the departure lateness caused by arrival lateness and that caused by other factors, the departure lateness of late arrivals is analyzed. Late arrivals are defined as those flights that arrive after their buffer times. The buffer time of a flight is the point of time defined by the end of the time interval that is the difference between the scheduled occupancy time of the flight and the time required to service the aircraft at a gate. It is measured in minutes after the scheduled arrival time of the flight.

One hundred seventy flights out of the 750 flights mentioned earlier were late arrivals. A scatter plot of the joint buffer and departure lateness of these flights is shown in Figure 2. The buffer lateness of a flight is defined as the difference between the flight's actual arrival time and its buffer time. The plot shows a strong correlation between departure lateness and buffer lateness. This would imply that if a flight arrives t min after its buffer time, a departure lateness close to t min will be the likely result. Figure 3 shows a scatter plot of scheduled and actual gate occupancy times of the same 170 flights. As can be seen from the plot, the actual occupancy times are significantly less than the scheduled occupancy times for most flights, which implies that, in the case of a late arrival, airport operators try to service the aircraft as quickly as possible to minimize delay, and consequently the actual gate occupancy time of the flight becomes disassociated from its scheduled occupancy time.

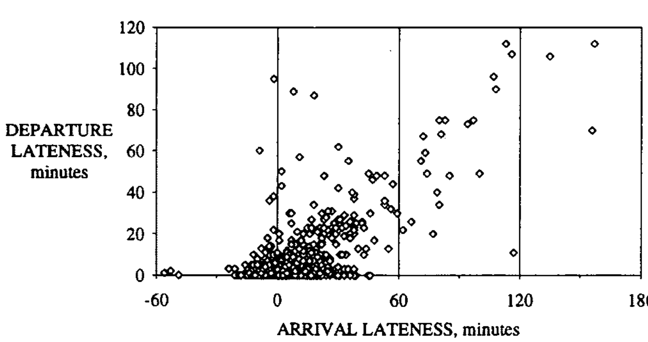

FIGURE 1 Joint arrival and departure lateness.

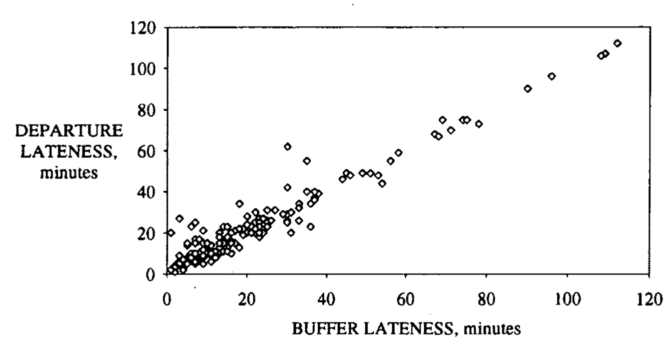

FIGURE 2 Joint buffer and departure lateness, late arrivals.

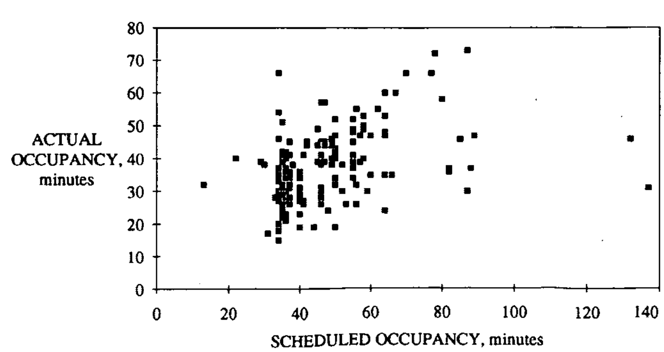

FIGURE 3 Actual versus scheduled occupancy, late arrivals.

STOCHASTIC MODEL OF GATE OCCUPANCY

Stochastic Derivations

Although flights are scheduled to arrive and depart at specific times, they usually deviate from these times. The reasons for deviation are numerous and unpredictable; therefore, deviations are assumed to be random phenomenon. For a given flight, let the scheduled arrival time define the time origin ($t = 0$). If $Y(t)$ is defined as a random variable whose value is determined by the event that the aircraft occupies a gate at time t, with t measured in minutes relative to the scheduled arrival time, this is a time dependent Bernoulli trial with

$$Y(t) = \begin{cases} 1 & \text{if the aircraft occupies a gate at time } t \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

Therefore, if an aircraft occupies a gate time t, it must have arrived before time t and left after time t, and the probability that the aircraft occupies a gate at time t is

$$P[Y(t) = 1] = P[(A \leq t) \cap (D + t_d \geq t)] \quad (4)$$

or

$$P[Y(t) = 1] = P[(A \leq t) \cap (D \geq t - t_d)] \quad (5)$$

where

A = random variable describing arrival lateness measured in minutes from scheduled arrival time,
t_d = scheduled departure time in minutes after scheduled arrival time, and
D = random variable describing departure lateness measured in minutes from scheduled departure time. Flights usually do not depart before their scheduled departure times; therefore $D \geq 0$.

As an illustration, the scheduled arrival time, the scheduled departure time, t_d, and buffer time measured in minutes after the scheduled arrival time, t_b, are plotted on a time axis in Figure 4.

Arrival times and departure times of flights that arrive before their buffer times can be assumed to be statistically independent. Arrival times and departure times of flights that arrive after their buffer times can be assumed to be correlated. In this context, two random events are defined: B is the event that a flight arrives before its buffer time, and B^c is the event that a flight arrives after its buffer time (complement of arriving before the buffer time). The probabilities of these two events can be expressed in terms of the cumulative distribution of the random variable A as follows:

$$P(B) = P(A \leq t_b) = F_A(t_b) \quad (6)$$

$$P(B^c) = 1 - P(B) = 1 - F_A(t_b) \quad (7)$$

B and B^c are mutually exclusive, collectively exhaustive events. Therefore, the probability of another event, $[Y(t) = 1]$, can be expressed in terms of those two events in the following manner

$$P[Y(t) = 1] = P\{[Y(t) = 1]|B\}P(B) + P\{[Y(t) = 1]|B^c\}P(B^c) \quad (8)$$

The occupancy of a gate by an aircraft at time t, given the aircraft arrives before the buffer time, $\{[Y(t) = 1]|B\}$, can be defined by the conditional joint event that the aircraft arrives before t and departs after t given arrival is before the buffer time. It follows that

$$P\{[Y(t) = 1]|B\} = P\{[(A \leq t) \cap (D \geq t - t_d)]|B\} \quad (9)$$

This expression can be evaluated by considering three non-overlapping time intervals: ($t < t_b$), ($t_b \leq t \leq t_d$) and ($t > t_d$). For $t < t_b$, the probability that an aircraft occupies a gate is simply the probability it has arrived because, by definition, flights do not depart before their scheduled departure time t_d, and $t_b < t_d$. For $t_b \leq t \leq t_d$, given the aircraft arrives before the buffer time and, by definition, does not depart before its scheduled departure time, the probability that the aircraft occupies a gate at time t equals unity. For $t > t_d$, given the aircraft arrives before the buffer time, it has therefore arrived before the scheduled departure time, and the probability that it occupies a gate at any time t greater than t_d is simply the probability it has not yet departed. In summary,

$$P\{[Y(t) = 1]|B\} = \begin{cases} F_{A|B}(t) & \text{for } t < t_b \\ 1 & \text{for } t_b \leq t \leq t_d \\ 1 - F_{D|B}(t - t_d) & \text{for } t > t_d \end{cases} \quad (10)$$

where

$$F_{A|B}(t) = F_A(t)/F_A(t_b) \text{ for } t < t_b,$$
$$= 1 \text{ for } t \geq t_b,$$

and $F_{D|B}(t)$ can be estimated directly by considering the departure lateness of flights that arrive before their buffer times.

The occupancy of a gate by an aircraft at time t, given that the aircraft arrives after the buffer time t_b, $\{[Y(t) = 1]|B^c\}$, can be defined by the conditional joint event that the aircraft arrives before t and departs after t given arrival is after the buffer time. It follows that

$$P\{[Y(t) = 1]|B^c\} = P\{[(A \leq t) \cap (D \geq t - t_d)]|B^c\} \quad (11)$$

This expression can be evaluated by considering two non-overlapping time intervals: ($t \leq t_b$) and ($t > t_b$). For $t \leq t_b$, given arrival is after the buffer time, the probability that an

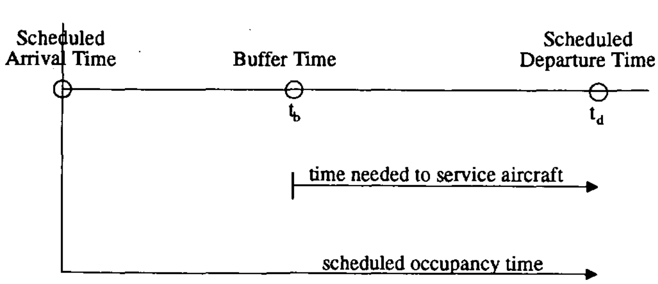

FIGURE 4 Representation of scheduled arrival and departure times in reference to buffer time.

aircraft occupies a gate is simply zero. For $t > t_b$, since, as explained earlier, the actual occupancy time of a late arriving flight (i.e., one that arrives after its buffer time) is disassociated from its scheduled occupancy time, the flight's actual departure time can be determined more accurately by its actual arrival and occupancy times than by its scheduled departure time and departure lateness. Let H be a random variable defined as the actual occupancy time in minutes of a late arriving flight. The probability of a gate occupancy can then be defined as

$$P\{[Y(t) = 1]|B^c\} = P\{[(A \leq t) \cap (A + H \geq t)]|B^c\} \quad \text{for } t > t_b \qquad (12)$$

where the right-hand side of the equation can be written as

$$P[(A \leq t)|B^c] + P[(A + H \geq t)|B^c] - P\{[(A \leq t) \cup (A + H \geq t)]|B^c\} \qquad (13)$$

Since H as defined cannot be negative, the last term of the expression must equal unity, therefore,

$$P\{[Y(t) = 1]|B^c\} = \begin{cases} 0 & \text{for } t \leq t_b \\ F_{A|B^c}(t) - F_{A+H|B^c}(t) & \text{for } t > t_b \end{cases} \qquad (14)$$

where

$$F_{A|B^c}(t) = 0 \text{ for } t \leq t_b$$
$$= \{[F_A(t) - F_A(t_b)]/[1 - F_A(t_b)]\} \text{ for } t > t_b$$

The cumulative distribution $F_{A+H|B^c}(t)$ can be obtained at any time t greater than t_b by summing the probabilities of all pairs $[(a,h)|B^c]$ for which $(a + h)|B^c \leq t$. For all times less than the buffer time t_b, this cumulative distribution is zero by the definition of $A|B^c$ and $H|B^c$.

The approximate shape of the function $P[Y(t) = 1] = p(t)$ is shown in Figure 5 along with the functions $P\{[Y(t) = 1]|B\}$ and $P\{[Y(t) = 1]|B^c\}$. This function of time increases from zero, starting at some point before the scheduled arrival time of the flight, and reaches a maximum near the scheduled departure time and then decreases.

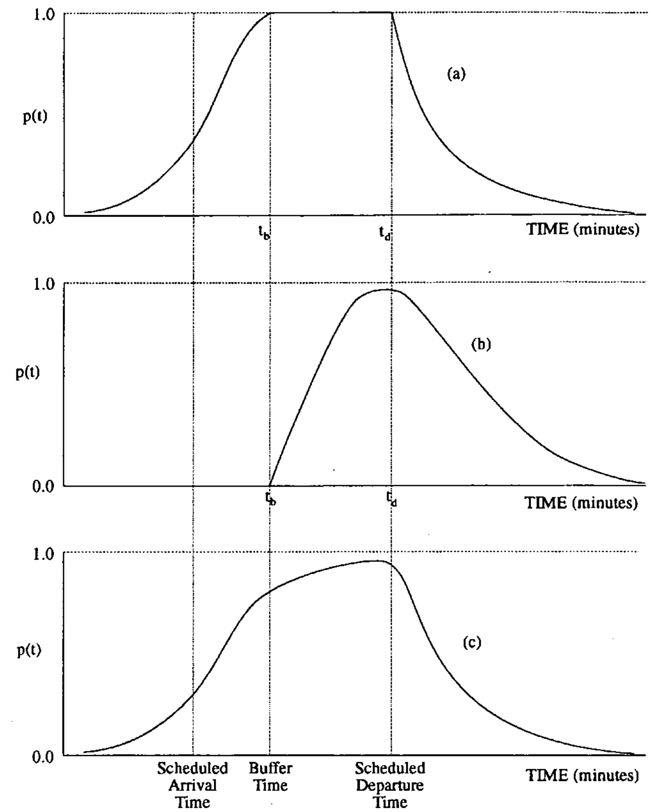

FIGURE 5 Schematic development of random variable $Y(t)$: (a) $P[Y(t) = 1|B]$, (b) $P[Y(t) = 1|B^c]$, (c) $P[Y(t) = 1]$.

Special Cases

So far, only flights that have arrival, departure, and buffer times (i.e., turnaround flights) have been considered. The discussion can be extended to cover originating and terminating flights. At a given time t, the probability that a gate is occupied by an aircraft that stays at the gate overnight and departs in the morning (i.e., a morning originating flight) is 1 for $t \leq t_d$, and $[1 - F_D(t - t_d)]$ for $t > t_d$. During the day, aircraft are brought from hangars to gates at some time before the scheduled departure times of originating flights. The time an aircraft is brought from the hangar to a gate before the flights' scheduled departure time depends on the type of aircraft (i.e., wide, narrow, or small body) and the flight sector (i.e., domestic, international). This time can be assumed to be a constant t_1 for each aircraft type and flight sector. It follows that the probability that a gate is occupied by an aircraft, when the flight is originated during the day, is zero for $t \leq t_1$, 1 for $t_1 < t \leq t_d$ and $[1 - F_D(t - t_d)]$ for $t > t_d$.

At a given time t, the probability that a gate is occupied by an aircraft that arrives last and stays at the gate overnight (i.e., an evening terminating flight) is $F_A(t)$ for all t. During the day, aircraft are towed off gates at some time after the arrival of terminating flights. This time can also be assumed a constant t_2 for each aircraft type and flight sector. The probability that a gate is occupied by an aircraft, when the flight is terminated during the day, can be calculated as $[F_A(t) - F_A(t - t_2)]$ for all t.

Occupancy of Aircraft Gates by Time of Day

On any given day, each scheduled flight i has a unique $Y_i(t)$, which depends on the flight's scheduled arrival and departure times, aircraft service time, and its behavior relative to these times. If s_i is defined as the scheduled arrival time of the i^{th} flight, the expectation of the random variable $Y_i(t)$, which is assumed to be Bernoulli at any given time t relative to the scheduled arrival time, is

$$E[Y_i(t)] = P[Y_i(t - s_i) = 1] = p_i(t - s_i) \qquad (15)$$

and the variance of the random variable $Y_i(t)$ is

$$\text{Var}[Y_i(t)] = p_i(t - s_i)[1 - p_i(t - s_i)] \qquad (16)$$

The total number of aircraft occupying gates at time t on a given day can now be defined as

$$N(t) = \sum_i Y_i(t) \quad (17)$$

The expectation of the random variable $N(t)$ is

$$E[N(t)] = \sum_i E[Y_i(t)] \quad (18)$$

The variance of the random variable $N(t)$ can be calculated as

$$\text{Var}[N(t)] = \sum_i \text{Var}[Y_i(t)] + \sum_{i \neq j} \text{cov}[Y_i(t), Y_j(t)] \quad (19)$$

Numerical Illustrations

As illustrations of how the model can be used to calculate the probability that an aircraft occupies a gate at time t and the expected value and the variance of the number of aircraft occupying gates at time t the following two examples are presented:

Example 1

In Example 1, a flight is scheduled to arrive at an air terminal at 12:00 p.m. and to depart at 13:00. The aircraft service time is 45 min. The flight's buffer time can be calculated as [(13:00 − 12:00) − 45 = 15 min after the scheduled arrival time], that is, 12:15. The probability that the flight arrives before its buffer time is $F_A(15)$. The probability that the aircraft occupies a gate at 12:45 given it has arrived before the buffer time is 1. The probability that the aircraft occupies a gate at 12:45 given it has arrived after the buffer time is $F_{A|B^c}(45) - F_{A+H|B^c}(45)$. Data collected to analyze the flight's behavior relative to its schedule indicated that $F_A(15) = 0.820$ and $F_{A|B^c}(45) - F_{A+H|B^c}(45) = 0.848$. The probability that the aircraft occupies a gate at 12:45 can now be calculated as

$$P[Y(45) = 1] = 1 * 0.820 + 0.848 * (1 - 0.820) = 0.973$$

Example 2

In Example 2, three flights are scheduled to be serviced by an air terminal during a given day. The probabilities that each one of these flights occupies a gate at 12:45 p.m. were calculated using the model as $p_1(12{:}45) = 0.973$, $p_2(12{:}45) = 0.562$, and $p_3(12{:}45) = 0.310$. The expected value of the number of aircraft occupying gates at 12:45 is

$$E[N(12{:}45)] = 0.973 + 0.562 + 0.310 = 1.845 \text{ aircraft}$$

If the flights are assumed to behave independently of each other, the variance of the number of aircraft occupying gates at 12:45 can be estimated as

$$\text{Var}[N(12{:}45)] = 0.973(1 - 0.973) + 0.562(1 - 0.562) + 0.310(1 - 0.310) = 0.486 \text{ aircraft}^2$$

APPLICATIONS OF MODEL

Empirical Realization of Model

Actual operation of aircraft gates at Terminal 2 of Toronto's Lester B. Pearson International Airport has been used to test the performance of the model. The number of gates available to accommodate passenger aircraft at Terminal 2 is 36. Twenty-eight of these gates can accommodate narrow-body aircraft (B727, B737, DC8, DC9) and wide-body aircraft (B747, B767, L1011, L15, DC10). The remaining eight gates can accommodate only small aircraft (CVR, DH8, B10, B99). The data used in the exercise were developed from summaries and logs of daily operations kept by Air Canada, the prime occupant and owner of Terminal 2 gates. Only passenger aircraft that have been assigned to terminal gates were included in the data. Aircraft that have been assigned nonterminal gates (cargo aircraft) were not included.

To put the proposed model in an operational form, it is necessary to describe each flight's behavior relative to its schedule and buffer time. Data limitations made this impractical; therefore, it was important to find, if possible, the common characteristics of some identifiable group of flights and assume that all flights within the group behave in a similar, though random, manner. Analysis of data collected at Terminal 2 showed that flights of different sectors and different aircraft types behave in different manners relative to their schedules. Accordingly, flights were categorized into five groups based on aircraft type and flight sector where transborder flights are those departing to or arriving from the United States:

1. Narrow-body aircraft, domestic flights;
2. Narrow-body aircraft, transborder flights;
3. Wide-body aircraft, domestic flights;
4. Wide-body aircraft, transborder and international flights; and
5. Small aircraft, domestic and transborder flights.

Scheduled arrival and departure times and actual arrival and departure times of flights in each of the five categories were recorded for 30 days of operation in October and November 1988. Arrival lateness, departure lateness, and actual occupancy time distributions were then developed for each category. As an example, Figure 6 shows arrival lateness distributions of the five categories of flights. Aircraft service and buffer times were determined from Air Canada's gate planning guidelines. Using these data, an estimate $\hat{p}_i(t)$ of the function $P[Y_i(t)]$ was obtained for each scheduled flight i on Thursday, January 14, 1988, and estimates of $E[N(t)]$ were calculated, using the model, at 1-min intervals. These estimates were compared to the sample mean $\bar{x}_{N(t)}$ calculated from gate occupancy data of 9 weekdays: Monday, January 11 to Friday, January 15 and Monday, January 18 to Thursday, January 21, 1988, and to the scheduled gate occupancy.

As shown on Figure 7, estimates of $E[N(t)]$ are in agreement with $\bar{x}_{N(T)}$'s for most of the day. Both estimates differ significantly from the scheduled gate occupancy during busy periods (1:00 to 3:00 p.m. and 6:00 to 8:00 p.m.). During these periods, deviation of flights from the schedule causes the actual required number of gates to exceed the number

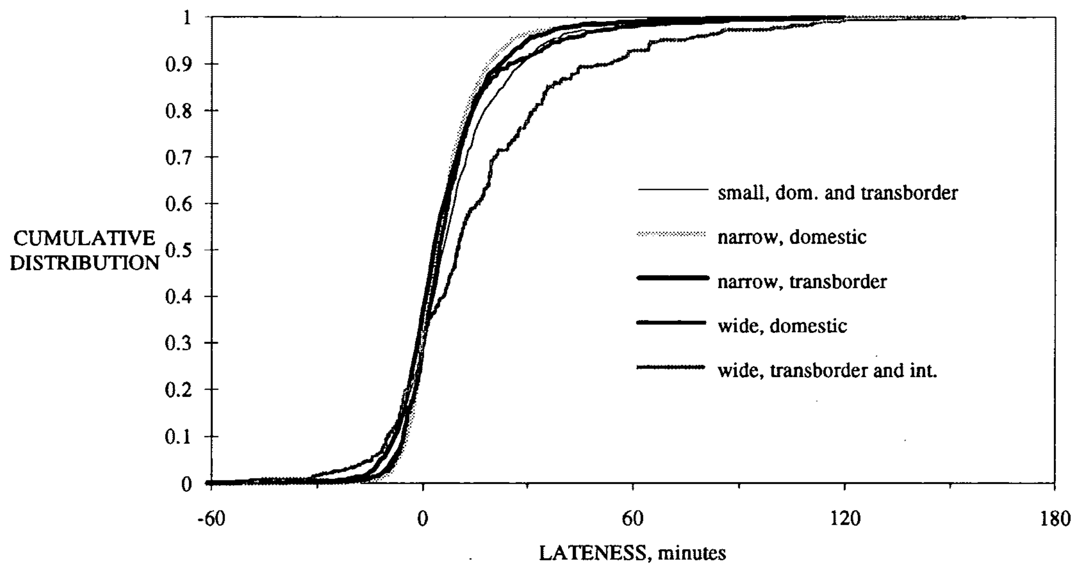

FIGURE 6 Arrival lateness distributions, all aircraft.

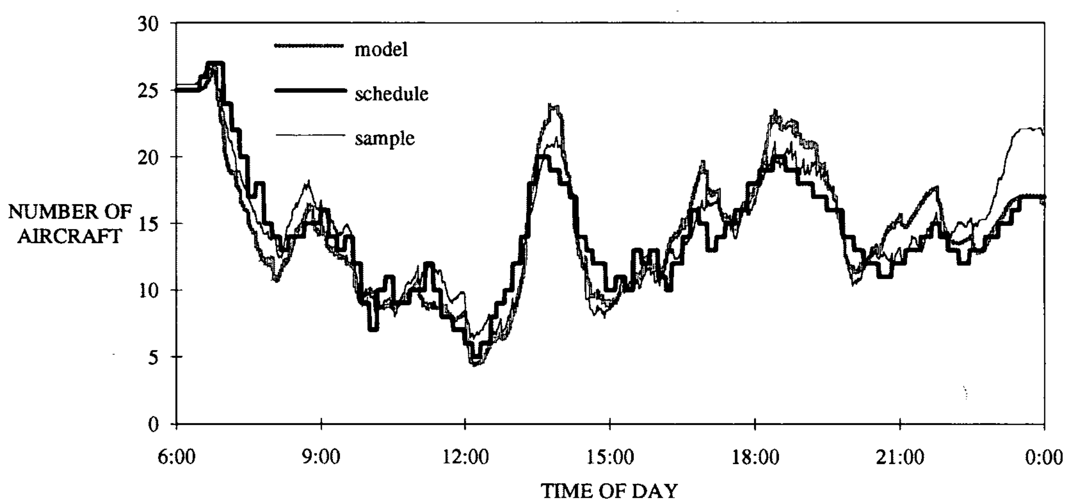

FIGURE 7 Gate occupancy.

specified by the schedule. The maximum scheduled gate occupancy from 1:00 to 3:00 p.m. is 20 aircraft. Both estimates of gate occupancy show higher values during this period.

The variance of the number of aircraft occupying gates at time t, $\text{Var}[N(t)]$, depends on the degree of correlation existing between flights. One extreme assumption is that of uncorrelated flights. The variance then becomes

$$\text{Var}[N(t)] = \sum_i \text{Var}[Y_i(t)] \tag{20}$$

Another extreme is to assume flights to be perfectly correlated and the variance is

$$\text{Var}[N(t)] = \sum_i \text{Var}[Y_i(t)] + \sum_{i \neq j} (\text{Var}[Y_i(t)])^{1/2}(\text{Var}[Y_j(t)])^{1/2} \tag{21}$$

Figure 8 shows estimates of $\text{Var}[N(t)]$ for both cases and the sample variance, $s^2_{N(t)}$. The estimate of $\text{Var}[N(t)]$ under the assumption of no correlation is consistently smaller than the sample variance. This implies that some kind of positive correlation occurs between flights. However, this correlation is small as indicated by the magnitude of the sample variance relative to the estimate of $\text{Var}[N(t)]$ under the assumption of perfect correlation.

Gate Requirements at Airports

At a given time t, the random variable N describing the number of gates occupied by aircraft can be thought of as the sum of a large number of independent, but not identically distributed, random variables each of which has a small effect on the sum. It follows from the central limit theorem that N is

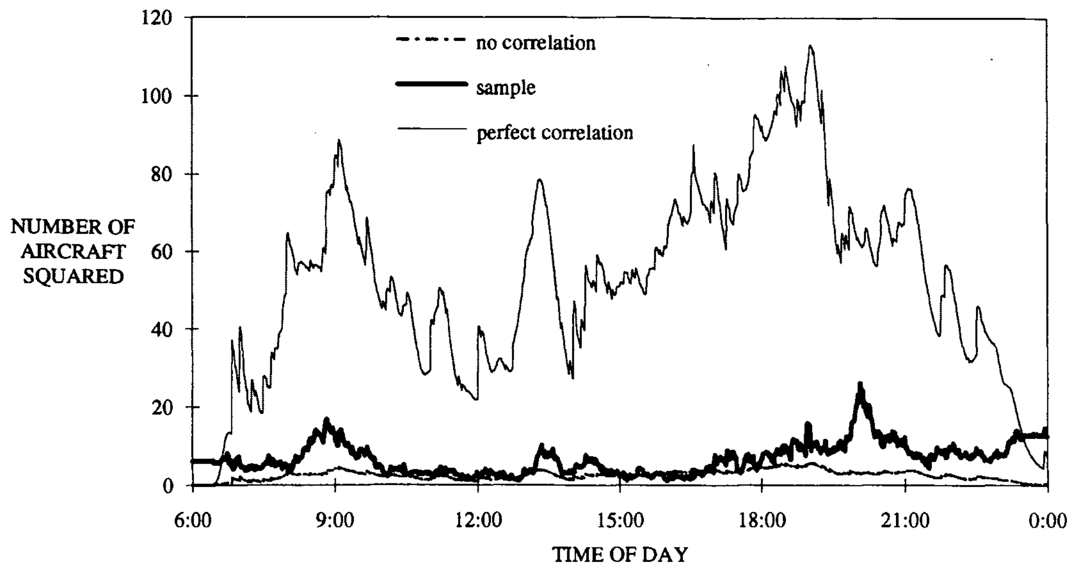

FIGURE 8 **Gate occupancies, estimated variance.**

asymptotically normal with mean $E(N)$ and variance $\mathrm{Var}(N)$. In this context, the number of aircraft gates required at time t can be calculated such that the probability that the demand for gates exceeds this number is very small, say 0.05. This is the value n such that

$$1 - F_N(n) = 0.05 \tag{22}$$

In terms of Z, the standardized normal (0,1) distribution, where

$$Z = [N - E(N)]/\sqrt{\mathrm{Var}(N)} \tag{23}$$

one should calculate n such that $F_z(z) = 0.95$. It follows that $z = 1.645$ and

$$n = E(N) + 1.645\sqrt{\mathrm{Var}(N)} \tag{24}$$

The maximum value of n over time of day provides an estimate of the required number of aircraft gates.

Equation 24 assumes a common gate use strategy (first-come, first-served discipline). Exclusive use of gates by particular air carriers or by flights of certain sectors is another gate use strategy used at many airports. Under such a strategy, Equation 24 can be rewritten for flights of each carrier or sector k, as

$$n_k = E(N_k) + 1.645\sqrt{\mathrm{Var}(N_k)} \tag{25}$$

The total required number of gates can then be obtained by aggregating the maximum values of n_k's over time of day.

Gate Requirements at Terminal 2 of Toronto Airport

A strategy of using gates exclusively for flights of a particular sector is currently adopted at Terminal 2, Lester B. Pearson International Airport. Fifteen of the 28 available gates that can accommodate both wide- and narrow-body aircraft are dedicated to domestic flights: 8 to transborder flights, and 5 to international flights. Under this strategy and for the schedule of the previous section that represents a typical week-day operation, gate requirements estimated using the procedure described in the preceding comply with the available number of gates. This is expected because the schedule has presumably been designed to account for the available gates and the adopted strategy of their use. For the same schedule, a common use strategy (first-come, first-served discipline) results in a saving of four gates as compared with the existing strategy. An exclusive strategy under which a group of gates is dedicated to Air Canada flights and the remaining gates are used by other air carriers requires a total of 27 gates. Sixteen of these gates are required by Air Canada and the remaining 11 by the other carriers.

Analysis of Bank Operations

Many airports are used by airlines as collection-distribution centers for their passengers. Flights are brought in and dispatched in banks (groups). The purpose is to facilitate transfer of passengers and baggage between flights in the same bank. If the banks are spaced apart such that interactions between flights of different banks are minimal, gate requirements can be estimated from the scheduled occupancies by taking the size of the largest bank plus one or two gates to account for variations. As the spacing between banks decreases, however, gate requirements increase because of deviation of flights from their schedules. The question is how close the banks could be scheduled without causing an excessive increase in gate requirements. Consider, for example, a schedule that consists of two banks of the same size, say, 25 flights each. Each flight has a scheduled occupancy time of 60 min and all flights are of the same sector and of the same aircraft type. Gate re-

TABLE 1 Gate Requirements under Bank Operations

Spacing Between Banks (min)	Maximum E[N(t)]+1.645√VAR[N(t)]	Required Number of Gates
60	35.88	36
70	29.18	30
80	27.21	28
90	26.09	27
100	25.95	26
110	25.85	26
120	25.71	26
130	25.66	26
140	25.66	26
150	25.66	26

quirements, under a common gate use strategy, for different time intervals between the two banks are shown on Table 1. When the flights of the second bank are scheduled to arrive 40 min or later after the departure of the flights of the first bank, 26 gates are required. As the spacing between the two banks decreases, the required number of gates starts to increase and reaches 36 when the departure of the flights of the first bank and the arrival of the flights of the second bank coincide.

CONCLUSIONS

Two factors have been shown to influence demand for aircraft gates: the flights' schedules and their actual behavior relative to these schedules. The first factor provides a deterministic element to the process of generating demand and the second factor provides a stochastic element to this process. The stochastic gate occupancy model presented in this paper provides a plausible tool for estimating gate requirements at airports based on these two elements. However, improvements can be achieved by further investigation of the cause and the nature of correlation between flights.

The use of computer-generated nominal schedules for estimating loads on terminal facilities has become a common practice at many airports. These schedules are generated from annual forecasts by making assumptions about aircraft fleet mix and load factors. The procedures of the paper provide a tool for incorporating the stochastic nature of flight arrivals and departures in the process of estimating gate requirements using nominal schedules.

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Evaluation of Airport Access Level of Service

N. N. NDOH AND N. J. ASHFORD

Access to airports is a major influence on passenger distribution among competing airports, and the level of service of the available modes also affects the observed modal split at each airport. Access to the airport is an integral component of the passenger's trip from origin to final destination. Improvements to terminal services and facilities to attract more passengers at an airport therefore need to be matched by ensuring that the level of service of the airport's access system is also adequate. Evaluation of level of service for airport landside, in particular the terminal, has been given research attention. Little research has been done to measure the level of service of access to airports, yet these measurements are required by airport management to improve access or formulate policies to influence modal split. Research in level-of-service evaluation to airport access using psychometric techniques is discussed. The raison d'être of the methodology is to provide scale values of level of service and use of the scales developed to investigate the effects of level of service on mode choice. The method was applied to a case study of access at a London airport. Results are presented in terms of passengers' satisfaction with various access attributes, and the scale deduced for access information indicates the need for better distribution of access information to air passengers.

Despite the continued large investments made to provide airports with terminal capacity and operational equipment, the flying public is familiar with the difficulties in reaching those facilities. With increases in traffic (airport and urban), the problem of access to the airport has intensified. The access system to most major airports is multimodal, composed of different car-based, public transport, and specialized modes (*1*). At most airports the private car is the most preferred mode of access. However increased use of cars poses difficulties for the management of efficient airport access because of the need to provide sufficient curb-side circulation around the terminals and parking spaces at the airport. These problems occur at airports with little room for further expansion.

Where there are competing airports within an airport hub system, access plays a key role in the distribution of passengers among airports offering flights to the same destination. It is no longer enough for airport management to encourage airlines to establish flights at an airport; there must also be provision of adequate airport access to ensure that passengers get to the airport on time to catch their flight. The preferred use of car-based modes by passengers and the envisaged resource requirements to cater to such increases make it necessary to investigate ways of influencing passengers to use high-occupancy vehicles (public transport) to enter the terminal. The switch in mode can be effected either by draconian measures, such as requiring advanced booking of parking spaces and other restrictions, or by improving the level of service (LOS) of public transport in comparison with the LOS of the private car. Before changes can be considered, it is essential to refine ways of measuring airport access level of service (LOS).

This paper presents a brief review of the literature of LOS measurement techniques. A methodology for airport access LOS evaluation is presented. The technique used is based on psychometric mathematical models for analyzing categorical data rooted in the law of comparative judgment. The method is then applied to the evaluation of airport access LOS measurement. Results and conclusions of the investigation are finally presented, including suggestions for improving the methodology.

PREVIOUS STUDIES

The concept of LOS measures as applied in air transport is based on highway transport measures that defined LOS in terms of gradations (*2,3*). A detailed review of these standards can be found in a paper by Ashford (*4*). Such measures have received much attention in the literature, particularly for airport terminals, and are used by organizations such as the BAA, Aeroport de Paris, and IATA (*5,6*). These standards owe their origin to traffic engineering concepts of capacity-volume ratios and are therefore criticized for being based on either space volume (space standards) or time volume (time standards). At a facility, time and space usually interact, resulting in LOS aspects such as overcrowding. Little information is given about how the standards are derived and how the assumptions are made in their derivation (*7*).

The current concept of LOS requires standards to be based on users' perception. Thus LOS is defined as the quality and conditions of service of a functional component or group of functional components as experienced by its users (*8,9*). Studies that have attempted to incorporate users' perception in the evaluation of LOS include works by Omer and Khan (*7*), Mumayiz and Ashford (*10*), and Mueller and Gosling (*11*).

Omer and Khan proposed the use of a utility approach to evaluate user-perceived value of LOS for airport landside subsystems (*7*). The utility function is defined as a weighted function of proposed attitudinal scales of each subsystem and objective performance measures of the subsystem. The method as presented was still conceptional. The direct use of survey rating scales in the model suggested in their paper is thought to be inappropriate.

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Mumayiz and Ashford (*10*) developed a passenger Perception Response (P-R) Model that attempted to tie the passengers' perception of LOS to the time spent in various terminal processes, using a three-category LOS structure: good, tolerable, bad. Application of the P-R model is inappropriate for application here because airport access is a multiattribute service system, involving different modes. A method that can evaluate more than one attribute at a time and scale qualitative attributes, such as comfort, is needed. P-R models also require a large data sample to obtain sensible grade partitions for any variable, such as processing time or waiting time at a facility.

More recently Mueller and Gosling (*11*) have proposed the use of psychological theories of perception scaling and categorical judgment to develop a LOS framework that permits passengers' perception of LOS to be directly integrated into the evaluation method.

In urban transport planning, there is no clear methodology for evaluating transport LOS based on passengers' perception. Time (in-vehicle and out-of-vehicle), cost, and service frequency are the main elements constituting LOS, with frequency measured in terms of schedule delay. Punctuality and regularity are approximated by using service frequency, and comfort is approximated by seat availability. A function of generalized cost is defined that weighs and sums these elements to give a unit measure of LOS. From the users' perspective, however, the determinants of airport access LOS are made up of factors other than time, cost, and schedule delay. These factors are (a) mode availability, (b) airport distance, (c) various components of journey time (waiting, processing, access to mode, mode transfer, in-vehicle, and egress), (d) level of convenience and comfort (ease of use and luggage handling, number of terminal and vehicle transfers, and parking availability), (e) mode reliability to ensure on-time arrival at the airport and reduced risk of missing a flight, (f) cost elements (fare for each mode, parking charge, and intrinsic cost of time), and (g) other factors (safety, privacy, and flexibility of mode). The decision context and background factors (available mode combinations) can affect perceived airport access LOS. The consequences of missing a flight and the value of the trip to be made cause these factors to be weighted differently by passengers than by ordinary commuters. This paper presents an alternative method to evaluate access and its application to access choice at an airport.

APPROACH TO SCALING ACCESS LOS

The adopted methodology for LOS evaluation is based on the psychometric scaling technique (*12,13*). The technique allows the scaling of passengers' perception of LOS attributes from categorical data. Categorical data are collected by most airports from passenger surveys in which passengers are asked to rate service attributes of preference, importance, or satisfaction. In applying the psychometric technique it is assumed that:

- A scale continuum, partitioned into k category boundaries, is defined. Any particular LOS attribute, j, has a unique perception scale value (U) that can be placed between two category boundaries. This scale value is unique irrespective of the person providing the scale measure.
- A category k in which the mean scale value U is placed has a lower and an upper boundary on the scale continuum. The lower boundary of the first category is minus infinity, and the last upper boundary of the last category is plus infinity.
- Any passenger providing a perception scale for an attribute j will ascribe a scale value V, which is related to the mean scale value U of j, the category boundaries t and $t + 1$, and a variance value specific to the passenger. The location of the category boundaries t and $t + 1$ are defined as composed of fixed components on the continuum and a random component ∂ that allows for variations in the interpretation of the category boundary k by different passengers. The spatial descriptions of V and t are shown in Figure 1.
- Over the whole population or a homogeneous sample, the sample mean scale value for any LOS attribute can be determined. The deduced scale is a discriminant process based on a specified probability distribution function. The normal distribution is assumed as this distribution for both the scale value and the category boundaries.

Further details to the theory and development of the model as applied to LOS evaluation are given elsewhere (*13,14*). The methodology was implemented as a spreadsheet model.

APPLICATION OF METHOD TO AIRPORT ACCESS

The successive category scaling technique was used to deduce attribute scales applied to airport access LOS attribute scaling at a London airport using survey data collected by Loughborough University personnel (*15*). Only enplaning passengers were surveyed and the observed modes were classified as private car, taxi, metro, public bus or coach, and multimode using British Rail (BR) trains and not using BR trains. These modes can be further disaggregated. Private car includes dropping off and parking at the airport and public bus includes coaches and airport buses. A multimode defines a trip using more than one mode that involved using the BR train (MBR) or not using one (NMBR).

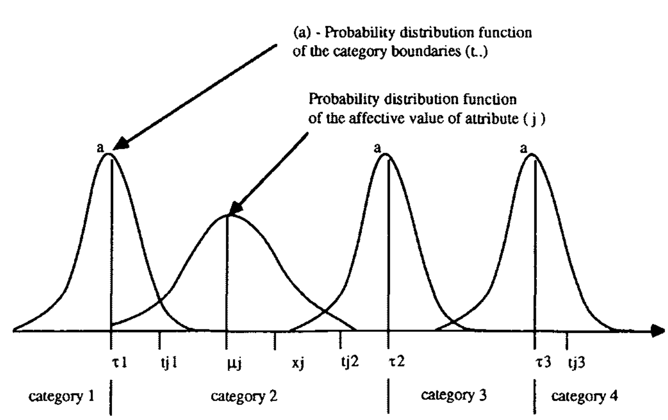

FIGURE 1 Spatial description of scale continuum.

A total of 165 passengers were interviewed in July 1991. This is a small sample considering the number of modes, the classification of passengers, and terminal throughput at the airport. Trip-related factors (such as journey purpose, flight type, time away, and place of origin) and socioeconomic characteristics of the passenger (such as income, age, profession, household size, and car ownership) influence modal split. The data sample did not allow the possibility of making such passenger segmentation for this analysis. The observed modal split was private car (39.1 percent), metro (15.9 percent), taxi (17 percent), hire car (4.2 percent), MBR (7.3 percent), NMBR (10.4 percent), and public bus or coach (6.1 percent).

To obtain successive category data for airport access LOS attributes on the basis of means of arriving at the airport, passengers were asked to express satisfaction with the factors listed in Table 1. The categories were graded "very satisfactory," "satisfactory," "indifferent," "unsatisfactory," and "very unsatisfactory."

RESULTS

The survey sample of 165 persons is relatively small for the size of the airport, the number of modes, and the list of variables considered. Therefore the results presented need to be read in this context because further validation is required using a larger sample. However the methodology and anticipated results are well demonstrated.

LOS Attribute Scales

By using the method of successive categories, LOS scales were obtained for the total passenger sample (Table 1). This model was tested to be used to predict the observed proportion from the survey data. The calculated total chi-square value with 22 degrees of freedom is 38.215 compared with a test statistic of 40.2 at a 1 percent significance level. The model parameters can therefore be used to predict the observed proportions. Table 1 shows the ranking of LOS attributes using the scale from the model. On the basis of the category boundaries, access to the terminal and luggage handling are two attributes rated to be very satisfactory. However satisfaction with luggage handling is something to be expected a priori because it is likely that passengers selected the mode most convenient to their amount of luggage. At the other extreme parking cost, applied only to private-car passengers, was rated as very unsatisfactory. Information on access was also rated as being unsatisfactory.

LOS Mode Scales

Passengers in the same group are expected to have similar perceptions of access LOS. The data sample from the survey was therefore defined according to the observed mode types (private car, taxi, metro, public bus or coach, car hire, and MBR and NMBR users). The survey ratings were again analyzed for each passenger group. By using the derived category boundaries, satisfaction ratings for each attribute by mode were determined, as presented in Tables 2, 3, 4, and 5, for private car, taxi, metro, and public bus or coach, respectively. The comparison shows that private-car users consider parking cost and access information to be unsatisfactory. Users of the other modes, except public bus or coach, considered information on access unsatisfactory.

The rating for information has major implications for modal split modeling. Commonly used modal split models, based on individual choice behavior, require that when passengers have a choice, the choice and options must be fully understood

TABLE 1 Scale Values of Airport Access LOS Attributes

LOS Attributes	Rank	μ_j	σ_j	χ^2
Ease of luggage handling	1	2.888	1.6427	4.266
Access to the terminal	2	2.6537	1.2806	0.999
Expected journey time	3	1.8335	1.3030	4.409
Comfort	4	1.7119	1.3340	6.478
Parking space	5	1.4141	1.1853	0.528
Convenience of interchange	6	1.2838	0.7980	3.745
Journey time	7	1.1988	0.8093	4.053
Delay and congestion	8	1.1038	0.8617	0.461
Economy of mode	9	1.0937	1.0306	4.161
Overall opinion of access	10	0.8930	0.7426	3.789
Access information	11	0.5655	0.8151	5.092
Parking cost	12	-0.7314	1.0076	0.234

Category boundaries (τ_j):

very unsatisfactory	$-\infty$	to	-0.6866
unsatisfactory	-0.6866	to	0.0
indifferent	0.0	to	0.7737
satisfactory	0.7737	to	1.6674
very satisfactory	1.6647	to	$+\infty$

TABLE 2 Ranking of LOS Attributes Rating for Private-Car Users

LOS Attributes	Rating
Convenience of interchange*	n/a
Ease of luggage handling	Very Satisfactory
Comfort	Very Satisfactory
Access to the terminal	Very Satisfactory
Delay and Congestion	Satisfactory
Parking space availability	Satisfactory
Economy of mode	Satisfactory
Journey time	Satisfactory
Expected journey time	Satisfactory
Overall opinion of access	Satisfactory
Access information	Indifferent
Parking cost	Unsatisfactory

(* n/a indicates an attribute not applicable to a mode).

TABLE 3 Ranking of LOS Attributes Rating for Taxi Users

LOS Attributes	Rating
Convenience of interchange*	n/a
Parking space availability	n/a
Parking cost	n/a
Access to the terminal	Very Satisfactory
Delay and Congestion	Very Satisfactory
Journey time	Satisfactory
Comfort	Satisfactory
Expected journey time	Satisfactory
Overall opinion of access	Satisfactory
Ease of luggage handling	Satisfactory
Access Information	Indifferent
Economy of mode	Indifferent

(* n/a indicates an attribute not applicable to a mode).

TABLE 4 Ranking of LOS Attributes Rating for Metro Users

LOS Attributes	Rating
Parking space availability	n/a
Parking cost	n/a
Access to the terminal	Very Satisfactory
Ease of luggage handling	Very Satisfactory
Delay and Congestion	Very Satisfactory
Economy of mode	Satisfactory
Convenience of interchange	Satisfactory
Journey time	Satisfactory
Expected journey time	Satisfactory
Overall opinion of access	Satisfactory
Access information	Indifferent
Comfort	Indifferent

(* n/a indicates an attribute not applicable to a mode).

TABLE 5 Ranking of LOS Attributes Rating for Public Bus or Coach Users

LOS Attributes	Rating
Convenience of interchange*	n/a
Parking space availability	n/a
Parking cost	n/a
Access to the terminal	Very Satisfactory
Ease of luggage handling	Very Satisfactory
Economy of mode	Satisfactory
Expected journey time	Satisfactory
Delay and congestion	Satisfactory
Journey time	Satisfactory
Access information	Satisfactory
Overall opinion of access	Satisfactory
Comfort	Satisfactory

(* n/a indicates an attribute not applicable to a mode).

(*16*). Passengers were asked whether they considered any other modes, which modes, and why they rejected them. If no options were considered, the respondents were asked whether they knew other ways of getting to the airport. Almost 70 percent of respondents said they had not considered another mode, and many said they had not investigated the options because habit or convenience led them to the mode they had used.

There are few studies in which passengers were interviewed about airport access to corroborate the results about the limitations and implications of information on modal split. Gosling noted that LOS information could affect the use of rail-based access to airports (*17*). Seneviratne and Martel reported that, of 227 passengers interviewed at Montreal Airport, 53 percent of the respondents saw information as the most important factor affecting quality of service everywhere in the terminal (*18*). The extent to which information is relevant to perceived LOS warrants further investigation. How would passengers respond to mode choice if they had full information?

Access to the terminal is rated very satisfactory by users of all mode groups. Table 3 shows some discrepancies in the rating of expected journey time compared with delay and congestion by taxi users. Where the rating for expected journey time was unsatisfactory, rating of delay and congestion would also be unsatisfactory. It is likely that for taxi users, congestion may have been understood to mean personal crowding instead of road congestion. Thus congestion had a better rating than expected journey time.

The usefulness of the obtained scale values can be extended by looking at the correlation of judgment between any two LOS attributes (*13,14*). Parking cost is related to the overall perceived LOS, followed by information and mode economy. (See Table 6.) A high correlation value was expected with journey time but this was not the case. These results should be read cautiously, because the number of passengers in the cross tabulation of the overall rating of access and each LOS used in each calculation varied between attributes. The survey sample was small. These calculations are illustrative and can be performed for the other modes with a more extensive data set.

EFFECTS OF LOS ON MODE CHOICE

The intramode scales reported above have different category boundaries and are inappropriate for mode choice analysis. The between-mode LOS scaling for each attribute, using the

TABLE 6 Correlation of LOS Attributes with Perceived Overall LOS Scale

Attribute	Correlation
Parking cost	0.980
Information	0.8215
Economy	0.5806
Delay	0.5193
Expected time	0.5193
Comfort	0.2986
Terminal access	0.1467
Journey time	0.0701
Parking space	0.0305

same category boundaries for each attribute, needs to be determined. Figure 2 shows sample scale values calculated to compare the different modes on the basis of mode economy, comfort, and access information. The full set of scale values for nine other LOS attributes is reported elsewhere (*19*).

It would have been ideal to have each passenger rate the current mode and options available to obtain the between-mode scales. This was not possible because of a time limit of 10 min per interview at the terminal. The scales by mode are approximate population averages assuming a normal distribution. It can be inferred that a passenger using a particular mode and subjected to the experiences of another mode would provide a scaling value close to the population average.

The mode ranking by attribute appears to conform to a priori intuition. Travelers consider taxis to be more expensive than other modes (see Figure 2). Comfort is rated best by private-car users, followed by taxi users. Metro and MBR are considered to be the least comfortable modes. Metro is rated uncomfortable because of crowding and difficulties associated with the stations (stairs, turnstiles). MBR is considered uncomfortable because it does not come directly to the airport and includes a trip on the metro. Passengers using public bus or coach rate access information best as compared with the other mode users. It would be expected that passengers choosing to use a public bus or coach know more about access alternatives, especially in London. Most private-car users considered using a train as their next best alternative. It is therefore disappointing to note that passengers using the multimode MBR rated information as unsatisfactory and worse than in other modes. Using these scales in mode choice analysis is discussed elsewhere (*13*).

CONCLUSION

Although the LOS of certain components of the airport has been researched, access, part of that component, has been neglected. This paper presents a procedure for assessing airport access LOS in a number of ways: by specific modes, analysis across modes, or examination of airport access attributes. The method uses a simplified data collection method that is cost effective because it allows a large number of attributes to be investigated within a short time. The interviewer does not need in-depth knowledge of how the attribute values are traded.

The results indicate that we can get quantitative perception scales from qualitative survey data. The method can therefore be used by management to evaluate the success of access improvements and judge how the improvements compare in other competing airports. It can be used to monitor passengers' attribute scaling over time compared with the actual objective measures of each attribute. A standard for access LOS can be established from such a large data set.

At most airports, improvements to access modes to the airport do not fall under the direct control of airport management. The method above can therefore be used to provide passengers' perception of access LOS to the airport. These measures help the discussion of likely improvements with those directly responsible. The scales are useful for investigating the relationships between perceived LOS and objective attribute measures and the relationship between LOS and airport access modal split. The ranking of attributes from this investigation has shown that most passengers were unsatisfied with the information they had about access. This poses a technical problem with using conventional choice models to analyze access modal split. The use of stated preference technique for data collection is recommended in investigating the effects of LOS on mode choice. Stated preferences allow those interviewed to have full information about alternatives and the LOS of each alternative. Although the sample collected here was small, the attribute scales and their ranking conform to intuitive expectation. To improve these results, a larger data sample should be collected to allow further passenger segmentation by mode, decision context, and passenger characteristics.

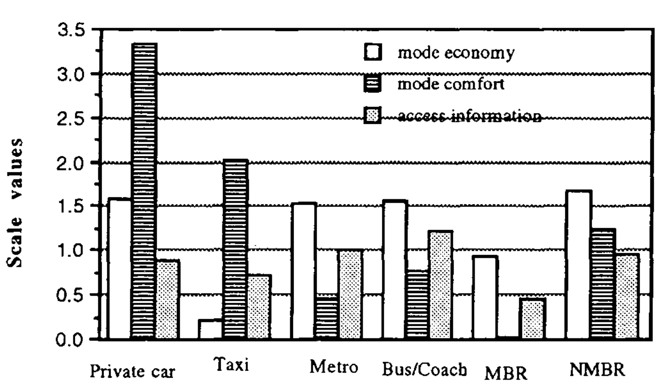

FIGURE 2 Between-mode attribute scales.

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Passenger Flow Distributions at Airports

U. VANDEBONA AND D. ALLEN

Models available for passenger traffic flow patterns at air terminals are reviewed, and a theoretical framework is proposed. Analogous models in other areas of engineering applications are investigated, and it has been attempted to take advantage of the prevailing experience in those fields. The relevance of the research into passenger flow distributions is explained and applications of such models described. The proposed model provides a sound starting point for queueing theory applications leading to analysis of congestion, delay, and travel times. The passenger behavioral aspects, such as the desire to reach the terminal early and apprehension related to missing flights, are taken into account. Data collected at Sydney International Airport have been used in comparison of the models.

This paper covers the model development phase of an ongoing research project carried out at the University of New South Wales, Sydney, Australia, into traffic flow distributions of airports. An in-depth discussion of modeling techniques available for handling the distribution of arrival and departure traffic on the road interface at airports is provided. Areas of application of the passenger arrival distribution, from the point of view of planners and traffic engineers, are described to highlight the relevance of this particular research project. The methodology developed in this paper has potential application to other types of modal interchanges where at least one mode is related to long-distance travel.

In conventional transport planning, the land use activity pattern of transport demand centers is taken into account to determine the traffic generation and attraction characteristics related to the transport center. A similar approach can be readily adopted in modeling the traffic flow of modal interchanges. For example, in a work by Wirasinghe and Vandebona (*1*) a regression method provided a relationship between the size of mass-transit stations and the intensity of the access passenger demand. A better estimate of the passenger traffic demand, however, may be made by considering the interrelationship and transformation of traffic flows among various modes linked to the particular interchange. This paper covers the modeling aspects that characterize that phenomenon.

The research work has two main areas of application: (a) terminal size estimation and (b) design of access road networks. Both require knowledge of passenger arrival and departure time distributions.

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BACKGROUND

Terminal Size Models

Airport size estimation typically relies on the intensity of passenger throughput data and magnitude of air traffic serving the terminal. The passenger throughput, with a level of service criteria, allows the estimation of the design size of the terminal area. The space requirements per person under varying level of service conditions have been reported elsewhere (*2–4*). Different levels of service are classified according to an alphabetic letter grade similar to that of highway engineering. A qualitative service classification scheme has been documented by various air transport authorities (*3,5*).

A simplistic method, which can be adopted in the sizing process, is to multiply a representative space requirement by the number of potential users. A refined calculation, however, will have to take into account the physical layout of the activities in the terminal building and the stochastic flow of passengers. Figure 1 shows a flow diagram of activities that are followed by passengers and aircraft at a typical airport. The figure shows that passengers progress through a series of holding areas for different activities. It is possible to estimate the average and maximum queue length at each of the activity areas by adopting the appropriate queueing model. The queue length measures reflect the passenger accumulation in the particular zone of activity. The space requirement for each zone of activity is computed, on the basis of space standard, for the particular activity under a specified level of service.

Consider that the maximum accumulations in each of the activity areas, because of a particular aircraft, are given by $S_1, S_2, S_3, \ldots,$ and S_n. If the space standards are given by $a_1, a_2, a_3, \ldots,$ and a_n for respective activity areas, the total space requirement is given by A^*, which can be computed as follows:

$$A^* = S_1 \cdot a_1 + S_2 \cdot a_2 + S_3 \cdot a_3 + \ldots + S_n \cdot a_n \quad (1)$$

The maximum accumulations ($S_1, S_2, S_3 \ldots$) reflect the operational aspects of the zone of activity. For example, if the movement from one activity space to another can be performed more quickly by increasing the processing rate, the queue processing slopes will be relatively steeper and thereby yield smaller accumulation values.

Additional space for passenger handling has to be allocated for passenger movement in links between various sections of the airport. Aspects of walking distance and its impact on the terminal design have been discussed elsewhere (*1,6–8*). In an ideal design it may be possible to neglect the distances passengers have to negotiate in various concourses, but geometric constraints often necessitate including such links, which yield significant walking distances.

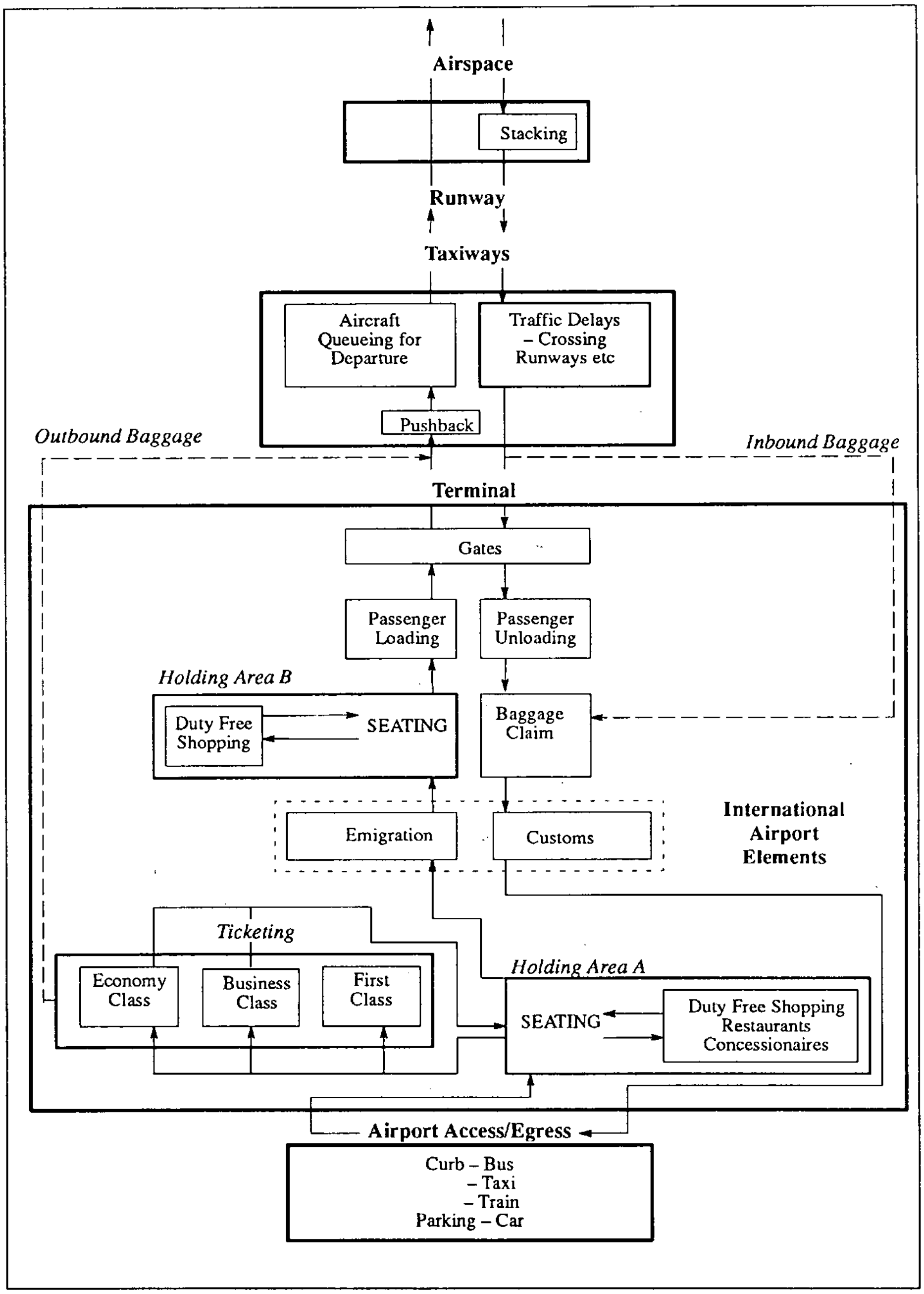


FIGURE 1 Airport activities.

It is also important to note that, as shown in Figure 1, the journey toward the aircraft consists of a different series of queues compared with the passenger journey from the aircraft.

Another technique available to handle the terminal sizing problem is simulation modeling (*9*). In simulation modeling, it is customary to adopt negative exponential service times and interarrival times in the queueing process. However, Bhatti (*10*) warns against the adoption of this particular distribution in queueing processes at airports on the basis of research work carried out in Nigeria. Thus there is a need for more field data to verify the range and applicability of the above models.

Airport Access Traffic Distribution

The other area of application of passenger arrival and departure time distributions is the development of models to estimate the temporal traffic distributions at airport access street networks. The aircraft arrivals and departures attract and generate traffic on landside modes serving passengers, well wishers, and employees of the airlines and airport. Knowledge about passenger arrival distribution and aircraft departure helps to better estimate vehicular traffic flows on access roads. Estimation of access road traffic flows is important for short-term purposes (area-wide traffic signal coordination) and long-term applications in planning of the road network.

An attempt to develop a regression model to forecast traffic flow on the access road on the basis of airline schedules at the Dallas–Fort Worth regional airport was reported by Dunlay and Wierzig (*11*). The inbound and outbound level of traffic prediction models were linear and took into account the number of aircraft enplanements and deplanements in 3 hr of airport operation (*11*).

At the Department of Transport Engineering of the University of New South Wales a number of graduate research projects have investigated aspects of access to airports. For example, Hupp (unpublished data) collected information related to the access and parking profiles at the Sydney Mascot Airport. Applications related to rail links were investigated by Doust (unpublished data), using a case study of a proposed remote airport. Recent work carried out by Pribadi (unpublished data) and Waluja (unpublished data) was aimed at developing computer models based on network algorithms and travel time formulations to estimate the travel times and level of congestion on the access road network.

Passenger Arrival and Departure Models

Models available for arrival and departure time distributions are reviewed. Work in this field provides descriptive explanations (*9,12*). Attempts to explain the above distributions in the form of mathematical relationships have been documented in works by Bhatti (*10*), Dunlay and Wierzig (*11*), and Tosic (*13*). It is evident that the models in this particular area can be classified into three main categories: descriptive, analogy, and regression models.

Descriptive Models

In some literature, the arrival passenger frequency distribution, relative to the aircraft departure time, is simply stated in a descriptive manner. In the descriptive method two main features have been associated with the distribution. The first part of the flow density distribution consists of a generally increasing function. The second part consists of a density function decreasing at a much faster rate than in the increasing period. Figure 2 shows the descriptive model in a graphical

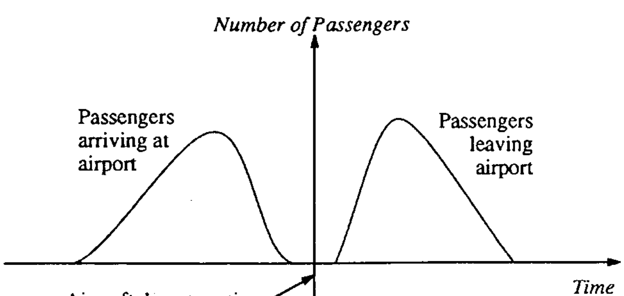


FIGURE 2 Descriptive model of arrival and departure time distribution.

manner. The frequency distribution of passenger arrival at curbside is indicated by the curve on the left-hand side of the figure, assuming that the aircraft is scheduled to depart at time zero. Note that the skew is to the left in this particular curve. The curve on the right-hand side represents the expected form of the distribution of passengers who are leaving the aircraft and the airport.

A detailed qualitative explanation about the spread of the passenger arrival time distribution at airports has been provided in a work by Odoni and De Neufville (*9*). It is argued that the arrival time distribution depends on the variability of travel time on the access road network and an individual's response to such variability. Because of renewed security procedures, some airports in Europe and North America cause the passengers to arrive at a predefined time before departure of the aircraft. The result is smaller space allocation per person because of the extra time in the airport imposed on the passengers.

Analogy Model

A useful analogy to the passenger distributions is found in hydrology. In particular, the runoff model includes concepts similar to the dispersion of passengers disembarking from an aircraft. The dispersion characteristics of passengers leaving aircraft is conceptually similar to the dispersion of water from a rain storm on a terrain with low permeability. Despite this similarity, the authors have been unable to find recent literature that adopted this analogy in airport landside traffic modeling. An early attempt to show the applicability of the unit hydrograph concept to data from a Brisbane, Australia, airport is documented in a work by Davidson et al. (*14*). Details of an applicaton of hydrograph analogy using data from Tullamarine Airport in Melbourne, Australia, are provided by Apelbaum and Richardson (*15*) and Apelbaum (*16*). However, as mentioned before, this particular analogy has not received further attention by researchers, perhaps because of lack of data to evaluate the method.

However, previous research work in which an attempt has been made to model the variability of travel time on road and public transport can also be considered relevant in applying this analogy. Dandy and McBean (*17*) provide a useful summary of previous research in this area and identified 12 research projects in which the travel time variations were monitored. The reported travel time surveys covered travel by car, bus, train, and by foot. About 25 percent of the research projects have concluded a log-normal distribution as a suitable model framework for travel time variations.

An advantage of pursuing this analogy is that modeling concepts related to different sizes of aircraft and various schedule patterns can be handled by exploiting the normalizing method referred to as unit hydrograph method in hydrological work. The runoff models are well established worldwide and an authoritative guide is provided by Pilgrim (*18*).

Table 1 presents the main similarities between the runoff model and passenger distribution model by identifying the corresponding features. Physical characteristics included in a runoff model, such as terrain slope and length of stream,

TABLE 1 Runoff Analogy Applied to Traffic Flow Discharged From a Demand Center

Traffic Flow	Runoff
Passenger disembarkation	Storm
Speed of movement in airport	Slope of the terrain
Free speed on the road	Slope of the main stream
Distance from airport	Length of the stream
Congestion attributes of the access roads	Channel roughness

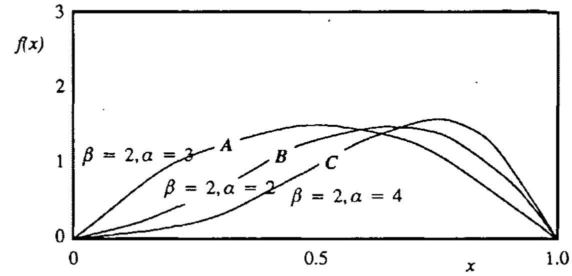


FIGURE 3 Beta distribution.

correspond to walking speed at the airport, vehicle speed on access roads, and distance from the airport.

To verify the applicability of the analogy it is necessary to monitor traffic flows on access roads to airports, relative to the aircraft arrivals. If it can be proved that the hydrograph analogy holds, then synthesizing traffic flow formulations for similar airport environments may be possible. In hydrological work, the synthesizing method has been adopted for ungauged catchments since the 1930s (*18*).

Regression (Curve Fitting) Models

Dunlay and Wierzig (*11*) document a regression-based model from the airline schedules at the Dallas–Fort Worth regional airport to forecast the traffic flow on access roads. Note that the researchers' attempt to fit theoretical probability distributions to various measurements of time showed a reasonable fit with gamma distribution for the vehicular flows bringing passengers to the airport relative to the departure time of the aircraft. (However, regression parameters have not been reported.) Corresponding distribution for vehicles carrying passengers from the airport is a log-normal shape. The applicability of the theoretical probability distributions at other airports has not yet been reported because of a lack of data.

The reasons previous researchers overlook beta distribution in attempts to find a standard probability distribution fit to the field data are not clear. The beta distribution has characteristics relevant for modeling in the area of passenger flow distributions. The gamma distribution and the log-normal distribution contain a long tail—difficult to explain in a traffic distribution model. On the other hand, the beta distribution can achieve the shape explained in the descriptive model because it contains a definite lower bound and upper bound in the independent variable axis. For example, consider the beta distribution using the conventional notation:

$$f(x) = \begin{cases} \dfrac{\Gamma(a + \beta)}{\Gamma(a)\Gamma(\beta)} x^{a-1}(1 - x)^{\beta-1} & 0 < x < 1 \\ 0 \quad \text{elsewhere} \end{cases} \qquad (2)$$

The frequency distributions are shown in Figure 3 for three different parameter value settings. A distribution similar to curve *C* in Figure 3 matches the descriptive model explained previously for access traffic. An advantage of the beta distribution is that it eliminates the possibility of a passenger arriving at an infinite time before departure of the aircraft. Such possibilities exist with the adoption of log-normal or gamma distributions and are therefore not representative of reality. However, the tediousness of the integration process to determine the cumulative beta distribution is a disadvantage of the beta model.

A number of students from the University of New South Wales have conducted surveys to investigate the suitability of the described models to Sydney Mascot Airport and other modal interchanges (Jayasinghe, unpublished data). A regular polynomial distribution of order 4 is seen to provide a better fit to data for Interstate travelers at railway and coach terminals in Sydney compared with distributions such as exponential, gamma, normal, and log-normal.

In general, the goodness of fit is improved with the increasing order of polynomials. The fourth-order polynomial was selected in this project as a compromise between the complexity of the resulting formulation and the degree of fit with field data.

Attempts to fit a similar fourth-order polynomial distribution to data obtained from the behavior of enplaning air travelers at the Sydney International Airport yield an equation of the following form:

$$Y_E = 2.399 - 0.318t + 8.888 \times 10^{-3}t^2 - 62.58 \times 10^{-6}t^3 + 0.129 \times 10^{-6}t^4 \qquad (3)$$

Y_E is the percentage of passengers predicted in a 3-min period (compared with total boardings) around time t min before the departure time for the flight. For deplaning passengers the corresponding equation follows:

$$Y_D = 0.727 - 0.562t + 56.08 \times 10^{-3}t^2 - 1.213 \times 10^{-3}t^3 + 7.464 \times 10^{-6}t^4 \qquad (4)$$

A weakness of the polynomial models is that unacceptable negative values result in troughs within the function.

MODIFIED POLYNOMIAL METHOD

A polynomial form developed by the authors attempts to satisfy the characteristics of the descriptive models and maintain mathematical simplicity essential for developing the cumulative distribution for further queueing theory analysis.

The model characteristics identified are:

- Frequency distribution of passenger arrival time at the airport relative to the aircraft departure time is skewed to the left for embarking passengers, whereas the skew is to the right for disembarking passengers.
- There is a distinct earliest and latest time related to arrival of embarking passengers and departure of disembarking passengers.

Consider the function $y_1(t)$ in Figure 4. This particular function has the quadratic equation:

$$y_1(t) = a_1t^2 + b_1t + c_1 \qquad 0 \le t \le T \tag{5}$$

In the equation, t represents the time variable. a_1, b_1, and c_1 are coefficients. It is evident that $c_1 = 0$ as the function passes through the origin. Therefore, the function can be rewritten as:

$$y_1(t) = a_1t^2 + b_1t \qquad 0 \le t \le T \tag{6}$$

Then consider the function $y_2(t)$ a quadratic formulation described in the same range but with a function value of zero at time T. $y_2(t)$ is given in the following:

$$y_2(t) = a_2(T - t)^2 + b_1(T - t) \qquad 0 \le t \le T \tag{7}$$

The product of the above two functions yields a distribution that agrees well with the descriptive model. This particular function follows:

$$R(t) = y_1(t) \cdot y_2(t) \qquad 0 \le t \le T \tag{8}$$

By expanding, it can be shown that

$$R(t) = a_1t^2(a_2\alpha - b_2\beta) + b_1t(a_2\alpha - b_2\beta) \tag{9}$$

where

$$\alpha = t^2 - 2Tt + T^2$$

and

$$\beta = t - T$$

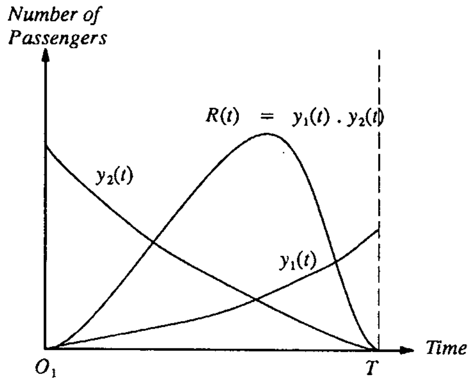


FIGURE 4 Representation of polynomial model.

There are a number of important characteristics of the above function for arrival and departure time distributions. They are explained in the following section.

When skew to the right is required, as in the distribution of inbound passenger arrival times, the coefficients of these equations take the following pattern:

$a_1 > 0$, $b_1 = 0$, $a_2 > 0$ and $b_2 > 0$

or

$a_1 > 0$, $b_1 \ge 0$, $a_2 = 0$ and $b_2 > 0$

or

$$a_1 > a_2 \text{ and } b_1 = b_2 \tag{10}$$

On the other hand, when skew to the left is required, as in the distribution of outbound passenger arrival times, the coefficients of these equations take the following pattern:

$a_1 > 0$, $b_1 > 0$, $a_2 > 0$ and $b_2 = 0$

or

$a_1 = 0$, $b_1 > 0$, $a_2 > 0$ and $b_2 \ge 0$

or

$$a_1 < a_2 \text{ and } b_1 = b_2 \tag{11}$$

Table 2 gives the range of skewness of the $R(t)$ function for different combinations of parameter values. The skewness is computed in the conventional manner by calculating the first, second, and third moments of the particular function. The table provides a useful guide for selection of the parameter values when the skewness expectations are known from field information.

Furthermore, the cumulative distribution, $A(t)$, can be developed by integrating the function $R(t)$.

$$A(t) = \int_0^T y_1(t) \cdot y_2(t)\, dt \qquad 0 \le t \le T \tag{12}$$

By expansion,

$$A(t) = a_1t^3(a_2\alpha_{n=5} - b_2\beta_{n=4}) + b_1t^2(a_2\alpha_{n=4} - b_2\beta_{n=3}) \tag{13}$$

where

$$\alpha_n = \frac{t^2}{n} - \frac{2Tt}{n-1} + \frac{T^2}{n-2}$$

and

$$\beta_n = \frac{t}{n} - \frac{T}{n-1}$$

Thus a relatively elegant cumulative curve is available by adopting the above model. For an inbound stream of passengers, $A(t)$ is typically the total number of passengers uplifted by the aircraft.

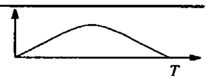
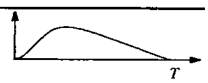
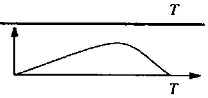
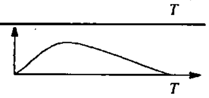
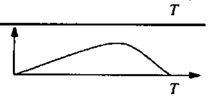
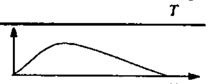
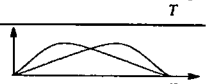
Through manipulation of the above equations, the average time $\bar{t}$ can be determined. This is shown below.

$$\bar{t} = \frac{T^2a_1(Ta_2 + 3b_2) + b_1T(2Ta_2 + 5b_2)}{Ta_1(2Ta_2 + 5b_2) + b_1(5Ta_2 + 10b_2)} \qquad (14)$$

Parameters for the above equations were derived using a least-square regression method. A partial differential technique was used to implement the least-square regression. For enplaning passengers:

$$y_{1E}(t) = 9.42t^2 - 8.38t \qquad (15)$$

TABLE 2 Upper and Lower Bounds of Skewness

Parameters	Range of Skewness (s_k) and Shape of $R(t)$	
$a_1 = a_2 = 0$	0 *symmetric*	
$b_1 = b_2 = 0$	0 *symmetric*	
$a_1 = 0$	$-\frac{2}{7} \leq s_k \leq 0$	
$a_2 = 0$	$0 \leq s_k \leq \frac{2}{7}$	
$b_1 = 0$	$-\frac{\sqrt{7}}{4\sqrt{2}} \leq s_k \leq 0$	
b_2	$0 \leq s_k \leq \frac{\sqrt{7}}{4\sqrt{2}}$	
$a_1 = b_2 = 0$	$0 \leq s_k \leq \frac{2}{7}$	
$a_2 = b_1 = 0$	$-\frac{2}{7} \leq s_k \leq 0$	
$a_1, a_2, b_1, b_2 \neq 0$	$-\frac{\sqrt{7}}{4\sqrt{2}} \leq s_k \leq \frac{\sqrt{7}}{4\sqrt{2}}$	

and

$$y_{2E}(t) = 0.0354 \times 10^{-6}(85 - t)^2 - 0.3900 \times 10^{-6}(85 - t) \qquad (16)$$

Similarly, for deplaning passengers, the corresponding equations take the following form:

$$y_{1D}(t) = 0.12t^2 - 2.50t \qquad (17)$$

$$y_{2D}(t) = 0.0641 \times 10^{-6}(223 - t)^2 - 0.0203 \times 10^{-6}(223 - t) \qquad (18)$$

The graphical forms of the above models are shown in Figures 5 and 6. The proposed polynomial method appears to underestimate the peak values. Even the regular polynomial model performs poorly closer to peak demand but provides marginally better answers in that region. As expected, the proposed model provides fewer estimates of unrealistic negative values from peaks compared with the regular polynomial model.

BEHAVIORAL INTERPRETATION

It has been attempted to establish by using field data the model properties useful in applications. Model calibration using field data currently being collected at the Sydney International Airport were also provided.

The $R(t)$ function is a product of a decreasing function and a monotonically increasing function. In practical terms, these two quadratic functions may be likened to the increasing sense of urgency that encourages passengers to arrive early and a decreasing liberty to arrive after a specified time. The sense of urgency, $y_2(t)$, and degree of liberty, $y_1(t)$, are combined to provide the arrival distribution, $R(t)$. This method of incorporating passenger concerns in traffic flow distribution is a novel concept developed during this research project.

Similarly, for deplaning passengers, the function $y_1(t)$ corresponds to the increasing sense of urgency to leave the terminal before a given time. Function $y_2(t)$ can be interpreted

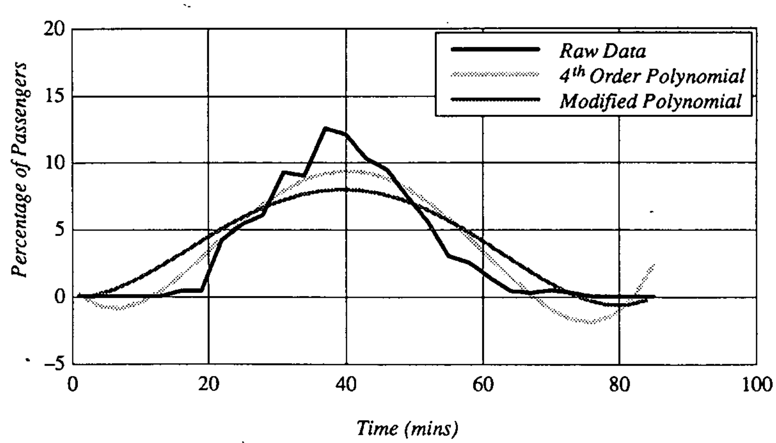


FIGURE 5 Comparison of enplanement models.

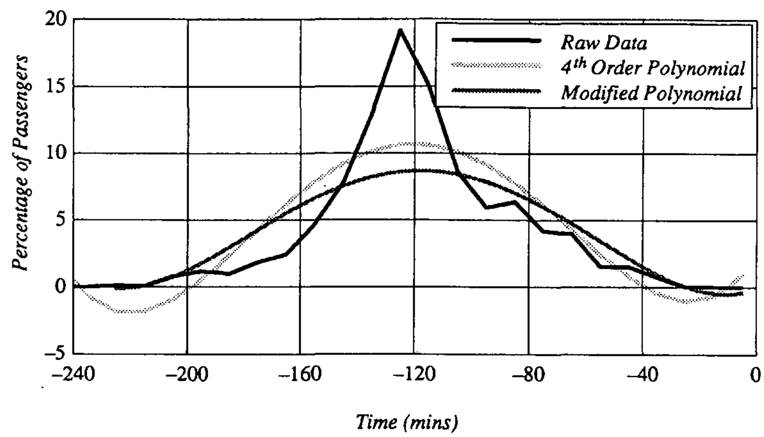


FIGURE 6 Comparison of deplanement models.

as the decreasing amount of liberty to leave the airport after the specified time.

The form of the functions $y_1(t)$ and $y_2(t)$ is assumed to be quadratic at this stage. It is possible to achieve the desired skewness with linear formulations for $y_1(t)$ and $y_2(t)$ but with little degree of freedom to manipulate curve fitting applications. On the other hand, adopting formulations of higher than second order may only introduce unnecessary computational complications with little improvements in accuracy.

CONCLUSIONS

It has been shown that the passenger flow distribution at modal interchanges, such as airports, is important for terminal sizing computations and estimation of access road traffic conditions. The terminal sizing problem is solved by applying queueing theory, level of service concept, and passenger flow distribution. On the other hand, it is seen that improved estimates of access road traffic conditions are available by analyzing the passenger flow distribution resulting from the traffic transformation effect of the modal interchange.

The passenger flow distribution, in terms of the arrival and departure times of passengers relative to the relevant aircraft movement, is presented in some literature only in a descriptive manner. This paper provides a review of passenger flow distribution models and identifies some modeling options overlooked by previous researchers. It is shown that the proposed analytical model can include the behavioral response of passengers toward the system characteristics.

ACKNOWLEDGMENT

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Beyond the Airport Terminal: People-Mover Technologies at Seattle-Tacoma International Airport

GERALDINE HECKENDORN POOR AND R. BURR STEWART

Seattle-Tacoma International Airport has been on the forefront of people-mover technology since the early 1970s and the installation of the Westinghouse Satellite Transit System (STS), an automated guided vehicle. The STS is integral in supporting the airport's efficient centralized terminal complex. The question today is How can such a system support further integration of the airport with the city beyond its automobile oriented landside access area? Historically, the interactions between the airport and private property have been minimal. The recent design development of automated people-mover systems (personal rapid transit or PRT) with small vehicles (three per vehicle) has presented urban planners and developers with a new option for meeting transportation needs. Whether and how such systems will be successfully integrated into a community remains to be seen. PRT is distinguished from the fixed guideway people mover already in use at the airport. How studies of the PRT concept were incorporated into studies of the airport transportation system and the complications involved in introducing PRT technology into a real urban environment are discussed.

Seattle-Tacoma International Airport (STIA) is midway between Seattle and Tacoma in Washington State. In the early 1970s major terminal expansion, a new parking garage, an airport access freeway, and an underground fixed-guideway transit system to carry people to outlying gates were built. The transit system uses group rapid transit (GRT) technology and can carry 40 passengers per car.

As the urban areas around Seattle and Tacoma grew into one metropolis, urban commuter traffic began to congest nearby roads. As a result, local transportation planners began looking for ways to improve transportation for the airport, businesses, and nearby neighborhoods. Potential new freeway access to the airport from the south and regional planning of a rail system (with an airport station) added to the local interest in additional development in the airport area. The recent design development of personal rapid transit (PRT) systems (small vehicles for one to three passengers, using light and less expensive elevated steel guideways) attracted airport area planners as a way to address local transportation needs and development potential.

STIA PEOPLE-MOVER SYSTEM

The STIA satellite transit system (STS) has provided a critical link between the main terminal and outlying aircraft gates for passengers, crews, well-wishers, and airport employees since 1973. The STS operates on three routes: two loops, each of which connects the main terminal to a long concourse and a satellite terminal, and a linear shuttle within the main terminal that links the two loops. STS is underground with all stations beyond the airport security checkpoints (see Figure 1).

Current Airport Operations

In 20 years, ridership has grown to almost 20 million passengers a year. The Westinghouse STS grew from two one-car trains in the 1970s to three two-car trains in each of the loops. A loop ride takes approximately 5 min to travel about 1.2 km (¾-mi). The shuttle has one car on a 3-min round trip along its 300 m (¼-mi) track. Headways (time between trains) on the loop routes are just over 1 min. An off-line maintenance area is also underground. Passenger safety is enhanced by a pre-recorded, multilingual greeting, closed-circuit television surveillance, and two-way voice communication by means of handsets in each car, linked to a central control facility.

The operating costs have risen (see Table 1), because of increased labor (supporting increased ridership) and triple power costs (although power represents only 2 to 4 percent of the total budget). In 1991 there were some operating changes. First, the system increased capacity by adding a third pair of trains to each of the loops. Second, for 4 months security restrictions because of the Gulf War resulted in fewer riders, because only passengers and crews were allowed beyond security checkpoints, where they boarded the STS to outlying gates. Even with those considerations, costs remain at a reasonable level, under 10 cents per passenger, despite an aging system, increased annual vehicle miles, and addition of a third train. The annual kilometers traveled have increased because of longer hours of operation and additional train capacity. System reliability has always been excellent.

To maintain modest operating and maintenance costs, the airport's system benefits from several diagnostic tools and cost saving procedures.

- A failure discrepancy report data base is maintained with historical data to track patterns of problems and help develop solutions.
- A vehicle data acquisition system (VDAS) provides an interface with each car's computer control system to help identify and assess problems. VDAS functions similarly to the black box in aircraft avionics to monitor operations.

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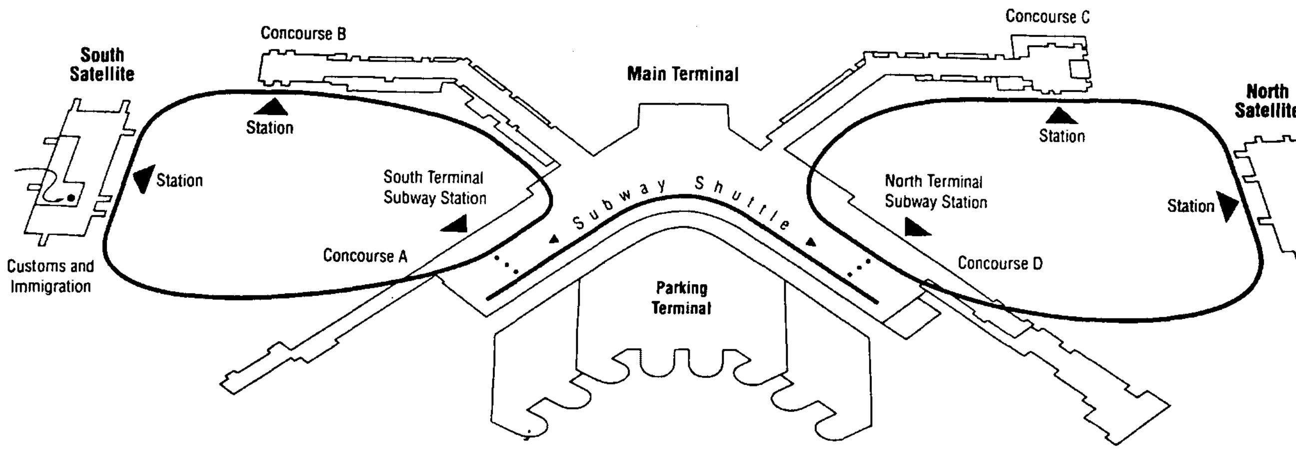

FIGURE 1 STS route.

- Thirteen electronics technicians are dedicated to the system. Operating engineers, mechanics, and electricians, who perform maintenance and repairs, are shared through the airport's maintenance department. Thus, only that portion of their salaries actually attributable to working on the transit system is billed to STS. This represents about 10 full-time equivalent positions.
- Because the system has spare vehicles, most work can be performed on all shifts. Routine maintenance can be scheduled by rotating vehicles, and unexpected breakdowns can be replaced with working vehicles.

Future Uses

Planners are studying now how best to meet airport capacity needs in the 21st century. Airport passenger forecasts for STIA (from 16 million annual passengers in 1990) call for 34 million annual passengers by 2010. Compared with investments recommended for other parts of the airport, the STS design will require only minimal upgrades: the addition of a third car per train and some controller and electronics improvements. STS can reach its design capacity of more than 9,000 passengers per hour per loop. The capacity is well beyond that expected for the system peak hours in 2010. Costs of the electronic upgrades will be approximately $6 million to $7 million.

PEOPLE-MOVING SYSTEMS

Urban Development Near STIA

STIA's eastern boundary is US-99, an older urban highway with typical strip commercial development. Four factors shaped urban development around the airport: (a) airport-related land uses, (b) transportation congestion, (c) suburban land uses, and (d) lack of strong local government.

Airport-Related Land Uses

Land uses around STIA are similar to many airports: hotels, parking lots, rental car agencies, fast food restaurants, warehouses, and air cargo facilities. These uses rely on low-density land development characteristic of the area (*1*). Whereas many of these uses face US-99 across from the airport, others are on cross streets, so that existing development is not strictly linear or coherently planned. About 30 nearby hotels (with more than 4,500 rooms) operate courtesy shuttle services to the airport.

About 25 parking lots provide more than 15,000 parking stalls: about one-quarter remote airport employee lots, one-quarter airport terminal area parking, and one-half commercial park-and-fly lots. Parking capacity is forecasted to be 21,000 spaces by 2010. Twelve parking lots operate shuttles

TABLE 1 SeaTac STS Operating Costs

	1980	1985	1990	1991 [1]
Annual Operating Cost	$800,000	$1,120,000	$1,265,000	$1,460,000
STS Passengers/year	11.0 mil	13.6 mil	19.3 mil	15.9 mil
Cost/passenger trip	$0.07	$0.08	$0.07	$0.09
Vehicle Kilometers	887,000	1,061,000	1,092,000	1,132,000
Cost/Kilometer	$0.90	$1.06	$1.16	$1.29
System Reliability	99.8%	99.9%	99.9%	99.9%

[1] 1991 includes two months' operations with an increase to three two-car trains, as well as 4 months' operation with only ticketed passengers and flight crew allowed beyond security check points.

into the city of SeaTac, a doughnut-shaped city around the airport.

Transportation Congestion

Traffic congestion in the local area is attributed to several sources: low-density land uses, regional traffic through trips, and airport passengers and related businesses. Interstate 5, 1 mi east of STIA, is the primary regional highway. Peak-hour slowdowns on I-5 encourage alternative commute routes, such as US-99, which passes the main entrance to the airport. The Municipality of Metropolitan Seattle (METRO), the area transit agency, provides some bus service. Transit and pedestrian facilities are not well used, and there is continuing reliance on automobiles and vans. A north access freeway connects about 60 percent of the travelers directly to I-5. The remaining 40 percent use local arterials to reach local facilities, or to travel east or south on I-5.

Suburban Land Uses

Land near the airport, not used for the purposes just described, is mostly low-density residences. Thus, the area's transportation problems include those of the residential community.

Local Government

Land around the airport was historically unincorporated under the land use control of the county. The recent incorporation of the city of SeaTac will lead to more detailed planning, but the current urban form is largely a result of past weak local government policies.

SeaTac's Agents of Change

Many changes have come to the area: increasing intergovernmental cooperation, new city government, and legislatively mandated proactive urban planning.

Recent developments may affect the potential for an airport people mover and have already led to a PRT feasibility study for the area. In 1989 government agencies and local developers jointly funded a feasibility study of a south access road to provide high-speed access for southerly airport traffic and local access to 200 acres of underdeveloped property planned as a business park. This potential mixed-use development could include offices, hotels, a civic center, airport support facilities, retail, and light industry.

In addition, incorporation of the city of SeaTac in 1989 brought local representation to more than 22,000 residents. To encourage economic development a flag pavilion and street banners were provided and the business park area was rezoned to urban densities.

Other agents of change are planning for a regional transit project, a state Growth Management Act and Commute Trip Reduction Law, the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), and the Clean Air Act. A people mover could improve accessibility for nonautomotive travel, which this recent legislation supports.

Feasibility Study

Many planners and developers were interested in increasing local mobility by reducing some local area trips on the roadway. In 1991 METRO organized a study (*3*) of an airport city people mover to answer three questions: What is the appropriate technology? What governance structure should implement a system? How should capital and operating and maintenance costs be paid? Joining METRO in the study were the city of SeaTac, Port of Seattle (airport operator), King County, and private businesses, such as developers, an airline, and some hoteliers from the study area. The committee's project management consultant was TDA of Seattle and the consultant team was led by BRW of Minneapolis.

Three transportation goals were defined: (a) public transit, (b) airport ground travel, and (c) city circulation. Public transit goals were to provide a collector-distributor system for regional transit system linkage and compatibility and matching appropriate technology with transportation function. The airport's goals were to serve remote employee-parking lots, remote airport employment, commercial park and fly lots, hotels, and rental car lots, and reduce congestion of the terminal access roads. Goals of serving employment centers (like the future Aviation Business Center), intercepting regional trips to the city, and reducing traffic congestion were important to the city. Secondary benefits would be reductions in vehicle miles traveled (VMT) and improved air quality. The land uses that a system would serve are shown in Figure 2.

The study's primary conclusion was that whereas shuttle buses can continue filling a people-mover function in the near term, a PRT technology application, if available, could provide even better mobility for many trips into the city. The necessary components of a PRT are as follows (*2*):

- Fully automated vehicles,
- Vehicles on a small guideway reserved for these vehicles,
- Small vehicles for only individual or small groups,
- Direct origin-to-destination service, and
- Service on demand not fixed.

To date, PRT technology is under development and has not been used anywhere; therefore, its feasibility cannot be assessed and capital and operating costs cannot be ensured.

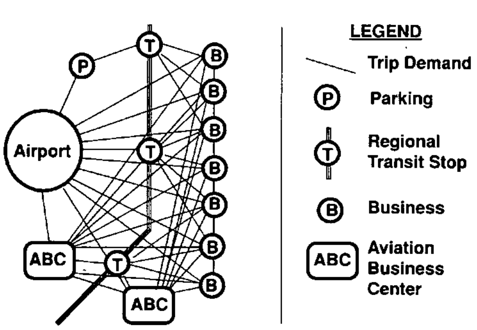

FIGURE 2 City of SeaTac travel patterns.

Study Findings

The three questions asked at the beginning of the study are explored. The question of technology relates to the city's urban form, types of development, special needs of the airport trip, environmental impacts, and technology development. The question of financing relates to patronage, costs, and potential financing. The question of governance relates to when the joint sponsorship retreats, who the operator should be and how the private sector would participate.

Technology

Three technologies were considered: jointly operated bus and van service, GRT, and PRT. An obvious choice is to extend the airport STS. Against expanding the 20-year-old system is that interim technology has improved. Furthermore, because the STS is underground, surrounded by a highly developed infrastructure, and beyond airport security, development costs would be high. This solution was thus deferred to a study of the range of options.

The city's form, like many airport cities, leads to trips with widespread origins and destinations (hotels and restaurants, remote employee-parking lots, off-airport rental car agencies, park-and-fly lots, and future development). Future uses would include one or more regional rail stations, the newly rezoned Aviation Business Center, and a regional park with a community activity center. Because most of these developments generate a few riders at a time (except the regional rail stations with several train loads disembarking at once), PRT's individual service and small footprint meet these considerations well.

Because a trip to the airport often involves time pressure and carrying luggage, the PRT's direct, individual service helps. In fact, PRT designs often show penetration of the building shell, allowing PRT boarding in a hotel lobby or the airport terminal. Environmentally, PRT proponents point out that guideways can be built offsite and elevated quickly with little construction disruption. Operationally, effects of noise and air pollution appear to be less than with the automobile. Because of the light, slim structural requirements for the guideway, other benefits of this technology are expandability, route flexibility, and minimal geometric restrictions. A proposed layout included 17 mi of one-way guideway, 31 stations, and 260 vehicles. Although a theoretical case can be built for PRT, there is no demonstrated system in operation. Clearly, the level of risk financing partners would be willing to assume will affect how much further development and testing will be necessary before investment.

Financing

Financial considerations are capital cost operation and maintenance costs, patronage, institutional and special benefits, and financing sources. The consultant team estimates $195 million to $316 million, on the basis of the technology developers' estimates, experience with other public transit projects, and contingencies. The range of costs is broad, because no system like this has been built. The technology developers estimate costs of vehicles ($450,000 each), guideway ($1.9 million/mi), stations (approximately $2.7 million), and maintenance and control (approximately $2 million). Add-on contingencies of 60 percent for development costs and 31 percent for engineering and administration have been estimated. A very low estimate is $113.7 million. However, because of experience with other systems, the consultant team recommended $195 million to $316 million, which nearly doubled the baseline costs.

The developers' operation and maintenance costs were estimated at $2.8 million in 1991 dollars. Although this is also very low compared with other technology systems in operation, it is inherent in the definition of PRT that lower operation and maintenance costs are incurred. Station security and landscaping are not included in the estimate. By comparison, the existing aggregate cost of the various shuttle buses and vans is $6 million to $12 million/year.

The team developed forecasts for patronage by means of a multistep process, from existing and planned land uses. The potential trip generators are employee and public park and fly lots, rental car lots, hotel, office buildings, the airport, and the regional transit station. From there, three more steps refined the forecasts. First land use "intensity" (number of trips generated per site), based on the ITE Trip Generation Manual, was estimated. Second, an "affinity" factor (likelihood of trips to start and end within the SeaTac people mover) was assigned. Finally, a "propensity" factor (likelihood of use of the people-mover modes under analysis) was developed. After ordering each site by rank by number of trips forecast, the consultants sited stations and linked them to minimize travel distance. Both PRT direct service and the very low wait and travel time increase the estimated patronage far above that of other technologies: 30,000 for PRT, 23,500 for GRT, and 18,600 for traditional bus. The PRT forecasted estimated trips between the airport and hotels are 34 percent, regional rail transfers 23 percent, and employee parking lots and future employment centers (at the ABC) 16 percent each. The remainder was passenger parking lots, recreational riders, rental car lots, and others. The cost per passenger is $2 to $4 per ride.

Suggested sources of public financing are city bonding capacity, county or METRO sales tax or motor vehicle excise tax, or airport passenger facilities charges. Some suggest pursuing a federal sponsorship as a demonstration project, in line with the philosophy of ISTEA. Private financing could come from property developers agreements or a local improvement district. Operators of existing shuttles could also discontinue the shuttles and apply cost to PRT funding.

The consultants reached the conclusion that, with an unproven technology, the cost ranges are wide and risk is high. If the risk capital is minimized, this location could demonstrate the viability of PRT technology.

Governance

The study recommended continuation of the joint sponsorship, under the METRO's lead, with the port and city as the other sponsoring agencies. Interlocal agreements could guide three follow-on phases:

1. Policy review and plan adoption;
2. Engineering, environmental, and financial plan; and
3. Construction, testing, and acceptance.

Only in the final operation stage would one agency have sole responsibility for the people mover. Joint sponsorship allows a centralized authority to draw on the staff and debt capacity of all three governmental agencies.

Private-sector participation is an extension of the governance issue. The developers and shuttle operators who participated in funding the study recognize the benefits of a PRT having access to their property. However, a group of smaller shuttle operators interviewed supported the status quo, especially if service to their businesses could not be guaranteed. A part of this hesitancy comes from two indirect marketing benefits of shuttle vans. A mobile billboard on vans that drive past travelers awaiting pickup exposes the travelers to the company names and logos. Second, for off-airport rental cars or hotel shuttle vans, passengers without reservations may take the first van they see. Only a Port of Seattle policy to ban shuttle on the terminal drives would ensure full participation, but that would be of questionable merit.

CONCLUSIONS

It has been seen that the STS people mover inside the airport, managed by a single operator for a single purpose, and behind a secure checkpoint has served the airport well. In transferring service outside the airport, there are theoretical indications that a PRT could meet the many goals and serve the most needs. However, there will be roadblocks. The undemonstrated reliability of PRT technology, the risk associated with financing, and the lack of solid support from competing community interests loom as significant issues to overcome. The authors look to further research in the industry to help answer some of these questions.

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Something Specious in the Air? Some Statistical Misconceptions in Aviation Safety Research

ARNOLD BARNETT

Because fatal air crashes are rare, it is often asserted that data about them cannot yield reliable inferences about patterns in air safety. That assertion may overstate, however, both the limitations of small data samples and the sensitivity of analytic outcomes to changes in starting assumptions. The issue is explored by discussing criticisms by a TRB panel and other commentators of two recent air-safety papers cowritten by this author. The goal is not to suggest that monitoring aviation safety can be reduced to studying fatal crashes, but to avoid an unnatural deemphasis on such crashes because of statistical misunderstandings. Beyond aviation, this may interest the broader group of transportation researchers who work with small data samples.

"I have been vilified; I have been crucified; I have even been criticized" (Mayor Richard J. Daley).

Not only do Americans care enormously about aviation safety, but their perceptions on the subject substantially affect their flying behavior. At critical times in spring 1986 and winter 1991, fear of terrorism cut transatlantic air travel by almost 50 percent. Anxiety about sabotage during the Gulf War caused the cancellation of millions of U.S. domestic air trips. And in the first 2 weeks after the 1989 DC-10 crash at Sioux City, Iowa, new bookings on the controversial DC-10 jet may have fallen by more than 33 percent (*1*,p.45).

Such circumstances lend exceptional interest to studies about risk patterns in U.S. commercial aviation, and many researchers have investigated the topic in one way or another. The author and his students studied the topic by analyzing data about fatal air crashes, generally weighting each such event by the proportion of passengers who perish in it. (*2*,p.1045;*3*;*4*,p.1;*5*,p.8;*6*,p.1). Although such fatal crashes are rare, it was argued that many striking phenomena in the data cannot plausibly be dismissed as random fluctuations.

Several papers describing this work have been harshly criticized for both the methodology employed and conclusions reached. Critics have included representatives of TRB, the National Transportation Safety Board (NTSB), FAA, the Air Transport Association, and the academic community. Even the television show *Saturday Night Live* hinted that one of the analyses was a bit preposterous.

No personal offense is taken at such negative assessments; professors wear bullet-proof vests under their academic robes. But the cumulative effect of the criticisms may be to suggest that it is unwise and perhaps irresponsible to perform safety studies that focus on plane crashes, the very events that air travelers fear most. This article takes issue with the critics and defends the "fatal event" approach to analyzing air safety. The goal is not to suggest that monitoring air safety can be reduced to studying fatal crashes; instead the goal is to avoid an unnatural deemphasis on such crashes because of statistical misunderstandings. To the extent that small-sample issues arise elsewhere in transportation research, the arguments in this paper are of wider relevance.

This article is concentrated on two recent manuscripts and the reactions they evoked (*4*,*6*). After a summary of each paper and major objections to the paper's content, attempts to rebut the objections one by one are offered. Other approaches to analyzing air safety are briefly discussed, suggesting that they might not be fully satisfactory.

AIRLINE SAFETY: THE LAST DECADE

Original Analysis

Written in late 1987 and published in early 1989, "Airline Safety: the Last Decade" (*4*) analyzed safety data for 120 airlines from 1977–1986. (The phrase "last decade" refers to the 10 years since the observation period for a previous MIT air-safety study (*2*). Contending that "the greatest fear in aviation is of being killed in a plane crash," it concentrated on statistics about the likelihood of that outcome. It noted that fatal-accident data are not perfect descriptors of system safety (or predictors of future safety) but pointed out that "no serious discussion about aviation risk can be oblivious to the objective trends in actual safety performance."

Most of its calculations were motivated by the question, If a passenger selected one flight completely at random within the set of interest (e.g., U.S. domestic jet flights in 1983), what is the probability that the passenger would be killed in an air crash? It argued that this death-risk-per-flight statistic was a more stable and illuminating measure of hazard than two widely used indicators of mortality risk, namely, deaths per billion passenger miles and deaths per million passengers carried. The last two measures weight each crash solely by the number of passengers killed, without reference to how many passengers were on board. In terms of system safety, however, a crash with perhaps 28 deaths might have very different implications if it reflected a high survival rate on a

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heavily crowded plane rather than a zero survival rate on a lightly loaded one. The death-risk-per-flight indicator avoids such ambiguity by weighting crashes by the percentage of passengers who perished.

Updating the earlier MIT study, the authors prepared mortality-risk estimates for three groups of airlines. These estimates and their counterparts for the earlier observation period are shown in Table 1. The table depicts large (and statistically significant) risk differences within each period among the three airline groups periods. But in a striking pattern of parallel improvement, all three groups cut the death risk by more than 80 percent between the earlier study period and the later one.

The authors also took account of an extraordinary development during the decade of study: the deregulation of U.S. domestic aviation. Before passage of the 1978 Airline Deregulation Act, "fears were expressed that, even though the new airlines brought into existence by the Act would be bound by federal safety rules, they would not match the accomplishments of established carriers with decades of experience" (*4*). Whether such misgivings were borne out by subsequent events was explored.

By focusing on the 8 years from 1979 (the first year of deregulation) to 1986 (the end of the observation), the authors computed mortality risk indicators for both established domestic airlines formed well before 1978 and for new entrant carriers spawned by deregulation. To make the comparisons fair, the authors considered only the 19 airlines among the new entrants that had all-jet fleets. Table 2 presents a summary of the key findings. The findings imply that death risk per flight from 1979 to 1986 was 12.2 times higher on the new jet entrants as on the established carriers. But air crashes were so rare in the study period that all risk estimates were intrinsically imprecise. Before treating the disparity in Table 2 as noteworthy, therefore, the authors performed a test of its statistical significance.

The analysis began with the conservative null hypothesis that new entrants and established carriers were equally safe. Nearly all domestic jet deaths from 1979 to 1986 occurred in five disasters that, on average, killed 95 percent of the passengers. The authors argued that, because the new entrants performed 4.7 percent of U.S. jet takeoffs and landings from 1979 to 1986, an equal-safety hypothesis would assign them a 4.7 percent chance of suffering any jet disaster during the period. Thus, their share of the five domestic jet disasters would be governed by a binomial probability distribution with five "trials" and parameter value of 0.047.

It emerged that the new entrants suffered two of the five crashes (40 percent of the disasters with 4.7 percent of the flights). That outcome does not absolutely prove that the new entrants were less safe than established carriers. But exact binomial calculations reveal that there is only a 1 in 42 chance that, solely because of bad luck, the new carriers would sustain as disproportionate a share of 1979–1986 disasters as they actually did. At the usual 5 percent significance level, therefore, the equal-safety hypothesis would be rejected, and hence

TABLE 1 Death Risk per Flight on Three Airline Groups and Two Successive Periods

Airline Group	1960-75	1976-86
Established U.S. Domestic Carriers	1 in 1.5 million	1 in 11.6 million
First-World Flag Carriers	1 in 430,000	1 in 4.4 million
Second/Third World Flag Carriers	1 in 67,000	1 in 390,000

Note: A nation's flag carrier was defined as its leading international airline. Mortality risk estimates for flag carriers were based only on their scheduled international operations.

TABLE 2 Death Risk for Flight on Two Groups of Domestic Jet Airlines (1979–1986)

Airline Group	Death Risk Per Flight	Percentage of Scheduled Domestic Flights, 1979-86
Established Carriers	1 in 11.8 million	95.3
New Entrants	1 in 870,000	4.7
All U.S. Jet Carriers	1 in 7.4 million	100.0
(All U.S. Jet Carriers, 1971-78)	1 in 2.6 million	100.0

the large discrepancy in Table 2 would be given both practical and statistical significance.

Table 2 also shows that, despite the relatively weak record of the new entrants, overall domestic death risk per jet flight fell from 1 in 2.6 million in 1971–1978 to 1 in 7.4 million in 1979–1986. But if deregulation had not occurred (hence no new entrants), the established carriers would presumably have performed virtually all domestic jet flights from 1979 to 1986. Assuming that deregulation neither worsened nor improved the 1979–1986 record of such carriers, it is suggested (Table 2) that, without deregulation, death risk per domestic jet flight from 1979 to 1986 would have been roughly 1 in 11.8 million (as opposed to the 1 in 7.4 million that actually prevailed). Because the increase was statistically significant, the assertion that overall domestic jet safety improved after 1979 despite deregulation and would have improved more without the policy shift was described as "plausible."

Reactions to Paper

"Airline Safety: The Last Decade" (*4*) attracted considerable attention, some of it positive. The death-risk-per-flight statistic was described as a conceptual advance, and the findings about the safety of established domestic airlines were well received. Attention was given to its calculation that, if a domestic-jet passenger chose one flight at random each day, the passenger would on average travel for 29,000 years before dying in a fatal crash.

The conclusions about airline deregulation, however, engendered a different response. The suggestion that the policy had had an adverse effect on safety was declared unreliable, and the analysis that produced it was portrayed as shallow or self-contradictory.

TRB Panel

Probably the greatest blow to the credibility of the work on deregulation was its sharp rejection by a TRB panel (7,Ch.5). The panel reached its negative verdict for three reasons.

1. It took issue with the definition of post-deregulation new entrants and, in particular, with the placement of World Airways in that category. [Because World Airways had amassed "extensive (pre-deregulation) experience in jet charter operations," the panel questioned the inclusion of its 1982 fatal accident in the new-entrant risk calculation.]
2. It noted that the inferences about new-entrant safety were derived from "only three fatal accidents" and hence saw them as subject to great instability.
3. It saw inconsistency in the authors' reasoning about the effects of deregulation:

> If deregulation was somehow responsible for allowing new entrant carriers, who provide about 5 percent of departures, to operate at a higher risk, then deregulation must also be given credit for the almost fivefold reduction in risk of the established carriers, who provide 95 percent of departures. Neither of these conclusions, however, seems plausible, especially in light of (other) studies. (7,p.169).

The panel said, "the risk definition and data aggregation techniques used by Barnett and Higgins do not measure the effects of deregulation on safety."

These words appeared in a comprehensive report on airline deregulation that has quite properly earned national distribution and respect. But, as much as the TRB panel conducted intellectually vigorous reviews of published literature, so should its own analysis be subject to spirited inquiry. It can be argued that all three of the panel's criticisms of the authors' work are fully rebuttable, and its rejection of the authors' conclusions should not stand.

There is room for argument about whether World Airways was really a new entrant (Point 1 of TRB). (The issue is whether operating international charter flights provides adequate preparation for scheduled domestic service.) But the debate need not be pursued, because it is irrelevant to the authors' conclusions. As noted, the authors weighted individual crashes by the proportion of passengers killed, and (as made clear) only 1 percent of those on board died when a World Airways jet skidded into Boston Harbor. Because its statistical test of the equal-safety hypothesis considered only the five full-fledged disasters from 1979 to 1986, it did not count the World Airways incident at all. Moreover, excluding World Airways data from the new-entrant calculation increases the estimates of the group's death risk per flight, from 1 in 870,000 during 1979–1986 to 1 in 855,000.

The reference to an unstable risk estimate (Point 2 of TRB) on the basis of only three fatal accidents is legitimate; indeed, to underscore the imprecision of the estimate, the authors calculated a statistical confidence interval for it. In context, however, the panel was tacitly advancing the stronger position that no serious conclusion about new-entrant safety can be drawn from a few fatal crashes. That is an overstatement.

Suppose that Air Scarsdale began jet operations between Westchester County and Hollywood-Burbank airports and that on its first day of service it lost two planes in fatal crashes. Can anyone imagine that passengers would deem it premature to judge Air Scarsdale's safety level based on "only two" disasters or that the carrier would even exist a second day? To put the issue more generally, even a few fatal crashes can be enormously discouraging if one would have expected none under normal conditions.

On the basis of both the disaster rate of established carriers and the number of annual flights performed by new entrants, one would have expected the new entrants to go 50 years before suffering the first disaster. In reality, they experienced two disasters in the first 8 years of service. Such an outcome is not inconceivable under the equal-safety hypothesis, but it is highly improbable. Few statisticians would see the outcome as leaving the hypothesis unscathed.

The final argument (Point 3 of TRB) was that if deregulation was somehow responsible for the relatively poor performance of new entrants, the policy must be given credit for post-1979 safety gains on the established airlines. But an important distinction must be made. It is plausible to tie deregulation to the new entrants' safety record because the end of regulation was responsible for their existence. Yet there is no corresponding requirement to treat deregulation as the main (or only) determinant of recent safety trends on other U.S. carriers. That position is obviously challenged by evidence in Table 1, which demonstrates that however impressive the recent risk reductions on the new entrants were no greater on a proportional basis than those on international flag carriers wholly unaffected by deregulation.

Other Reactions

In a detailed survey about deregulation's impact on domestic air safety, McKenzie and Womer reviewed the authors' analysis on the topic and found it wanting (*8*). They noted that the inferences about new entrants arose from "exceedingly few accidents," that 16 of the 19 jet carriers formed after deregulation had no fatalities from 1979 to 1986, and that the new entrants may have flown more dangerous domestic routes than did established carriers.

McKenzie and Womer also criticized the authors for dismissing the possibility that deregulation had improved safety on established U.S. airlines. Such progress could have occurred, they argued, because deregulation may have allowed more efficient and profitable operations and produced greater allocations of resources to safety by both government and airlines.

Two of these objections can be dealt with quickly. The response to the comment about "exceedingly few accidents" is the same as the one to the TRB panel's similar statement. The "dangerous routes" argument seems unpersuasive because all three fatal events that befell new entrants during 1979–1986 occurred not at obscure places ignored by established carriers but at the busy airports in Boston, Milwaukee, and Washington.

It is true that 16 of 19 new jet entrants had perfect safety records from 1979 to 1986. But that does not work against any argument advanced by the authors. The aim was to estimate the overall effect of the open-skies policy, and hence what was needed most was the average risk level among the jet "children" of deregulation. Estimating the group average neither implies nor requires that there be no airline-by-airline variation around the mean. At the same time, the "16 in 19" statistic is not strong evidence of heterogeneity in new-entrant safety. Collectively, the 19 carriers averaged one disaster per 850,000 jet flights. But the average new entrant performed only 90,000 flights from 1979 to 1986. Thus, even if the 1-in-850,000 risk level applied equally to all 19 carriers, the vast majority would have had no disasters in the 8 years studied.

As McKenzie and Womer report, the authors' paper quickly discounted the possibility that deregulation had made established carriers safer. But McKenzie and Womer's theoretical arguments on how deregulation increased air safety are not easily reconciled with familiar facts. If better monitoring by federal authorities improved post-deregulation safety on the established airlines, that achievement has gone unrecorded; the government's most conspicuous air-safety activity from 1979 to 1986 was to try to rebuild the air traffic control system after the firing of 11,000 controllers in a 1981 strike. And it seems odd to speak of the financial benefits that deregulation brought to established carriers; all of them lost money, and most suffered economic stresses so great that they were subsequently forced into merger, bankruptcy, or extinction.

On a more methodological level, Oster et al. (*9*) raised a challenge to the authors' analysis of deregulation. Although not referring to that work, these scholars questioned the soundness of the general procedure by which the authors tested the equal-safety hypothesis. Tests like those were "open to question," because they use data that "reflect the *ex post* universe of accident performance of airlines rather than a random sample of such performance" (*9*,p.81).

It is surely true that if one devises a hypothesis upon looking at certain data, there is something circular in using those data for a "test" of that hypothesis. Moreover, if events in the process under study affect the end point and the length of one's period of observation, or both, one gets a biased data sample and not a random one. But when neither of these conditions obtains, gathering data from a particular time interval can readily be construed as a form of random sampling.

Any hypothesis like the equal-safety conjecture is, after all, a description of what will happen in the long run. The events that occur over an innocently chosen short time span are only a random sample of those that would arise if the process were observed indefinitely. And, like the opinions of randomly selected citizens picked in a political poll, these events allow useful but imperfect inferences about the underlying pattern.

The authors choice of 1979–1986 as the observation period was not contaminated by any visible threats to randomness. The first year that domestic skies were deregulated was 1979, and 1986 ended a 10-year period since an earlier air-safety study at MIT.

Another objection to the authors' analysis was never raised: perhaps what had been observed was only a transient effect of deregulation, tied to the fact that new entrants were at the start of the learning curve. That possibility is not outlandish, but Table 1 shows that the higher risk levels of flag carriers in developing countries have proved enduring rather than ephemeral. In any case, if the new entrants had been economically successful, a continuing stream of newer entrants may have flowed to the start of the learning curve.

UNFORTUNATE PATTERN IN U.S. DOMESTIC JET CRASHES

Original Analysis

The death-risk-per-flight statistic was predicated on a completely random choice among flights. But passengers do not select flights at random: they appear in larger numbers on the average 747 aircraft than on the average DC-9 aircraft and in larger numbers on the Wednesday before Thanksgiving than on the third Wednesday in January. Such nonuniformities in demand, however, would not bias the death-risk estimate so long as passengers did not travel disproportionately on hazard-prone flights. The authors of "Airline Safety: The Last Decade" (*4*) took it for granted that this last caveat reflected only a remote possibility.

In 1990 Barnett and Curtis, authors of "An Unfortunate Pattern in U.S. Domestic Jet Crashes" (*6*), set out to dispense with the caveat altogether by trying to document that the domestic jets involved in major crashes were neither unusually large nor unusually crowded. These authors concentrated on established U.S. domestic carriers from 1975 to 1989. (Post-deregulation new entrants were excluded, it was explained, because nearly all of them were out of business by 1989 and thus their undistinguished safety records appeared to be of no continuing relevance.)

The authors defined a crash as being major if it killed at least 20 percent of the passengers. Focusing on the percentage rather than the raw number killed avoided a built-in bias toward large or crowded planes. If, for example, a crash were classified as major only if it took at least 250 lives, the "finding" that all major crashes occurred on wide-body jets would not be illuminating. Under this criterion, if a plane with two passengers crashed and one of them was killed, the crash would be designated as major.

Major crashes occurred from 1975 to 1989 that collectively accounted for 98 percent of domestic jet deaths during this period. The authors tested the following null hypothesis:

> The distribution of passenger loads for the 10 jets in major crashes was statistically indistinguishable from the corresponding distribution for all domestic jet flights from the time span 1975–1989.

Surprisingly, the data dictated the emphatic rejection of the hypothesis. The 10 planes in major crashes averaged nearly twice as many passengers as did other domestic flights from 1975 to 1989. Difference-in-distribution tests that compared the histogram of passenger loads on the 10 ill-fated flights with that of the other 60 million jet flights from 1975 to 1989 reached a strong conclusion: if the crashed flights had truly been a random sample from all domestic jet flights, the probability would be only about 1 in 5,000 that they would have carried as many passengers in total as they actually did. (In statistical parlance, the p-value of the observed pattern was 1 in 5,000).

The 10 planes that crashed had an average load factor of 84.7 percent, which was more than 25 percentage points higher than the average of 59.4 percent for all domestic jets over the period. Whereas individual jets exhibit wide variation in load factors, the detailed load-factor distribution renders it extremely unusual to be 25 points above average in a randomly drawn sample of 10 domestic jets. The upshot is that passengers did appear to fly in larger-than-usual numbers on hazard-prone flights. That finding undercuts one of the premises of the death-risk-per-flight statistic (although not the authors' (*4*) general conclusion about deregulation, which does not depend on that statistic).

Reactions to Paper

The paper by Barnett and Curtis evoked much press attention and disapproval. The director of research and engineering for the NTSB criticized the study's methodology and conclusions in interviews with the Chicago Tribune (*10*,p.1) and *Seattle Post-Intelligencer* (*11*,p.81). "When you are dealing with extremely rare events like major crashes," he explained, "you have to be extremely careful about extrapolating information." He made clear that he doubted that the researchers had displayed the requisite prudence.

Others joined in expressing strong objections to the paper. A spokesperson for the Air Transport Association (ATA) declared that the authors showed extremely poor judgment in choosing variables for the study. Noting that "there were months of the year when there were no crashes," she asked, "does that mean it's safer to fly in those months?" A spokesperson for FAA told the *New York Times* (*12*,p.A16) that the pattern discovered "must be a coincidence. We've investigated these crashes," he reported, "and we know their causes."

Such dismissive reactions were perplexing to the authors. The NTSB director had accused the authors of being oblivious to small-sample hazards but the authors devoted a full appendix to the subject in the paper. The authors applied several formal tests to the data, all of which gave full weight to the limited number of events under study. The procedures for drawing conclusions followed widely accepted standards of statistical inference.

A simple comparison offers some perspective on the strength of the authors' finding. If one tossed a coin 10 times and got all heads, one would presumably be highly skeptical that the coin was fair. Although 10 heads in a row from a fair coin is freakish (a 1-in-1,024 chance), it is far less so than picking 10 domestic jets at random and finding as many passengers as were actually aboard the 10 planes that crashed (1 in 5,000).

It is unclear why the ATA spokesperson criticized the authors for extremely poor judgment. The authors did not assume a link between crowding and safety at the outset but, on the contrary, hypothesized its absence. As to the query on whether air travel might be safer in some months than others, the concentration of snowstorms and thunderstorms in certain seasons suggests that the answer could well be yes.

It is not evident how to construe the FAA spokesperson's contention that coincidence explains the findings in the paper. If he means that the outcome reflects nothing more than fluctuations, the 1-in-5,000 probability estimate appears inconsistent with that interpretation. If he means that crowding per se did not cause any crashes, he is restating a point that the authors had made. (The *New York Times* subheadline about the work included the words "no casual link.") The authors had warned, however, that crowding could raise the probability that some other factor could lead to disaster (e.g., improperly deployed flaps) and argued that the risk-crowding correlation could be noteworthy even if causality is absent. If, for example, planes at rush hour are at unusually high risk of airport-area collisions, identifying that pattern gives information to passengers that they might use in deciding when to fly.

NBC's *Saturday Night Live* also got into the spirit of things by summarizing the authors' paper.

> An MIT study has concluded that more people die in planes with more passengers. For instance, in a plane carrying 220 people, 220 people would be killed. As opposed to a plane carrying 15 people, where only 15 people would be killed. A further study reveals that your best chance of survival is to fly in an empty plane (*13*).

RESPONSE TO CRITICISMS

If Barnett and Curtis (*4*) and Barnett and Higgins (*6*) have been subject to excessive criticism, why should that be of general concern? There are a few reasons.

It is said that nature abhors a vacuum, which in this context means that the enormous public interest in aviation safety will inevitably generate statistics on the subject. If direct estimates of the risk of being killed are successfully portrayed as deeply compromised, then proxy risk measures will come to the fore.

But these surrogate statistics may create new problems in the course of circumventing others.

The TRB panel questioned the Barnett and Higgins findings on deregulation in part because of the results of other studies. Only one study that the panel cited contrasted established carriers with new jet entrants (*14*,p.237). That paper noted that compared with established airlines, the new entrants spent larger portions of their operating budgets on maintenance and had slightly fewer accidents per million departures. In effect, the study treated maintenance expenditures and overall accident rates as superior proxies for "true" mortality risk than was the observed mortality risk over the same period.

But were those measures really superior? Maintenance's share of the budget seems an ambiguous measure of safety: the new airlines may have operated older fleets, been less able to take advantage of economies of scale, or spent maintenance money less wisely than their established counterparts. And if higher expenditures on maintenance mean lower ones on other essentials (e.g., pilot training), then safety could suffer rather than gain.

In emphasizing overall accident rates, the study (*10*) cited by TRB was following a common practice in air safety research. That circumstance lends particular importance to two events from the 1980s. The first involved an Aloha Airlines Boeing 737, which suffered an in-flight structural failure that practically destroyed the upper half of its fuselage. A flight attendant was blown out of the crippled plane, but the pilot managed to land it with no passenger injuries. The second took place on an Air Canada Boeing 767 that, because of a misunderstanding about whether its kerosene requirement was expressed in pounds or kilograms, literally ran out of fuel in mid-air. The pilots brought it down safely to an abandoned airstrip in Manitoba. Although the plane was damaged in the highly irregular landing, no passengers were hurt.

Both of these events meet a broad definition of accidents. But is it irrelevant that extraordinarily skilled cockpit crews saved all the passengers from airborne crises that could easily have killed them all. Arguably, the consequences of an accident say more about the safety of an airline's operation than does the existence of the accident. Yet such consequences get no weight at all in overall accident-rate statistics.

More generally, proxy measures for the death risk of flying may avoid such unpopular activities as inferences from small data samples. But the proxies typically entail questionable assumptions and blurring of salient distinctions. It is not obvious that they are more illuminating than direct measures of mortality risks. Some cures, as the saying goes, are worse than the diseases.

But, as a practical matter, do any conclusions drawn about the safety of air travel depend heavily on the way it is measured? Clearly, the answer can be yes as evidenced by the TRB panel's sharp contrast between the authors' findings and those from another study. Effects that are large and statistically significant under one measure may be nonexistent under another. The selection of a safety index, therefore, is a matter of more than aesthetic interest.

And, of course, the conclusions that one draws about prevailing safety patterns affect one's perceptions about how to reduce risk. The authors received several calls about the paper by Barnett and Curtis (*6*) from a senior captain at one of America's leading airlines. He reported that pilots and copilots alternate takeoffs at his carrier but that in inclement weather the pilot always takes the controls. He wants to adopt the bad-weather rule on fully loaded long-distance flights because of a reduced margin of error in dealing with takeoff emergencies. The authors' statistical findings, he reported, would be helpful to him in making his case.

Perhaps his airline and others will adopt the policy change he is seeking, and perhaps over the next quarter century, one jet takeoff crash will thereby be averted. That possibility alone suggests that the authors acted properly in reporting the pattern that they had observed. It also pointedly suggests that dismissing the finding out of hand might not be a risk-free option.

CONCLUDING REMARKS

Because fatal air crashes are rare, analyzing data about them means working with small samples. Small-sample data are volatile, and even apparently stark patterns within them may be nothing more than meaningless fluctuations. If the fatal crashes are partitioned into categories, slight changes in the classification rules might substantially alter cross-category differences.

Serious researchers recognize these hazards. But they also recognize that whereas small data samples are not inevitably useful, neither are they inevitably useless. By means of formal tests of statistical significance, calculation of confidence intervals for key parameters, and sensitivity analyses to see whether the findings depend substantially on particular decisions (e.g., on whether to classify World Airways as a new entrant), the researchers can realistically assess whether particular results are too imprecise to be credible. Statistically minded investigators understand that if a pattern is sufficiently extreme, a clear signal can be transmitted by even a small data sample.

Official reactions to studies about U.S. air disasters often appear defensive. But such defensiveness is misplaced: such studies do not disadvantage U.S. aviation but, on the contrary, constitute the most effective means of upholding the claim that established U.S. carriers are the world's safest airlines. It would be ironic if bodies like FAA, ATA, and NTSB succeeded in discrediting the form of analysis that tells us exactly what they are: perhaps the most successful organizations devoted to safety in the history of the world.

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DISCUSSION

TRB Task Force on Statistical Methods in Transportation (A3T51)

REVIEWER 1

Barnett and Higgins, in their work "Airline Safety: The Last Decade" (*1*), propose the *Q*-statistic and use it as the measure for reporting risk (and relative risk when comparing carrier groups). However, the article makes no real inquiry into the sampling distribution of *Q*, and as shall be discussed here, it appears to this reviewer that the authors underestimate the variability inherent in the risk elements.

All the hypothesis tests in the authors' work use binomial tests (randomization tests) on the frequency of "disasters." These tests are conditional upon a classification of fatal accidents as disasters and nondisasters. The classification occurs after the fact and any variability present in the proportion is disregarded. Overall the authors report 12 fatal accidents during the period 1977 to 1986, of which six are classified as disasters. Of the nine fatal accidents from 1977 to 1986 reported by the authors for trunkline carriers, four are classified as disasters, and for the period 1979 to 1986, three of (presumably) eight are also classified as disasters. For new entrant airlines, two of three accidents are classified as disasters. The disaster classification rates are 0.375 and 0.667, respectively, for established carriers and new entrants, and the hypothesis test in Section 7 of the authors' work is contingent on those observed rates.

There are certainly reasons to anticipate that differences in crew training and experience, equipage, and other factors might affect the expected survival rate in a given accident or in a population of accidents. On the other hand, even given the specific set of circumstances that attends a particular accident, the intuition of this reviewer is that mortality in the accident is still very much a matter of chance. The next three accidents are very much a matter of chance. The next three accidents occurring to new entrants, from 1987 on, for example, might well produce no disasters, or one, or three. The number of disasters arising from a specified number of fatal accidents is arguably binomial with an unknown parameter value that may depend on the type of airline or environmental risk factors. The variability of this binomial type of outcome should be incorporated when making inferences regarding disaster incidence. In addition, the equal safety hypothesis of the authors should include the supposition that the mean proportional mortality is the same for established carriers and new entrants, and (in this regard there is a small-sample problem) the supposition would not be rejected.

Similarly, the weighting factors used in constructing *Q* are random variables, embodying the "fluctuations . . . in the survival rate per incident," and in contrast to the dismissal of such fluctuations by the authors as second-order effects, this reviewer believes that they make a nonnegligible contribution to the variability of *Q* when the number of accidents involved in computing *Q* is small. Thus it is plausible, but not altogether clear, that the value 12.2 is the maximum likelihood estimate of the new entrants' risk multiplier (*1*,p.15), and if so, work remains to clarify the form of the likelihood. The 10 percent confidence range for the risk multiplier should also probably be wider than as calculated by the authors.

The *Q*-statistic does have some appeal as an estimator of death risk. It is apparently unbiased. It recognizes the clumping of mortality risk by accident and leads to a sample size (number of departures) that is more meaningful than the number of passenger-departures. However, a more satisfying approach to this reviewer would be to use a hierarchical model, assuming that fatal accidents arise as a binomial or Poisson random variable, and use a second random variate—beta, for example—to model the proportion of deaths, conditional on occurrence of an accident. Such an approach would seek to extract information from all the accident data, at least fatal accident data, instead of ignoring the low fatality accidents in making inferences about safety.

Despite the expressed reservations, it is still likely that the new entrants and established carriers exhibit a statistically significant difference in risk, and the authors are justified in asking that this difference be considered seriously, despite the small number of accidents overall. The reservations are not strictly speaking small sample issues, although the concerns are magnified by the small number of accidents. Rather, they are concerned with modeling technique, in the sense of identifying the proper sampling frame and assessing sources of variability in the sampling frame.

The propositions that are considered in Section 8 of the authors' work (*1*) appear to this reviewer to drift beyond the sampling framework within which the data were collected. Even if one shows that the new entrants have a death risk that exceeds the risk of established carriers, the contention that deregulation "raised by roughly 60% the average risk per flight for domestic jet travel" (*1*,p.16) is based on a causal proposition that is neither proven nor disproven by the data and previous analyses. In calculating the overall postderegulation death risk, the authors include six local jet carriers formed before deregulation: Aircal, Alaska, Aloha, Hawaiian, PSA, and Southwest. Together these carriers had over 600,000 revenue departures in 1986 (compare with 1.7 million departures on the new entrant airlines, 1979–1986, as given by the authors). To make an assessment of deregulation's impacts, it would be desirable to consider also the experience of these and similar carriers before and after deregulation. Would these former intrastate carriers be naturally aggregated with the new entrants (to the extent that they also experienced rapid growth) or with the established truck carriers? The point to be taken from the third criticism of the TRB panel discussed by Barnett in his paper is that discipline and consistency are necessary in the application of the control variable (i.e., deregulation). The authors make suggestive findings about the death risk of new entrants, and these findings are worthy of serious consideration, in spite of the reservations about sampling distribution and the small number of accidents. However, the manner of presentation by the authors, in the abstract and the final remarks, places relatively emphatic statements about risk on the marquee. The reservations to which Barnett reacts in his paper in part reflect reasonable concerns that the strength of the evidence in the data and the thoroughness of the analyses in the authors' work (*1*) do not yet warrant a determining influence on public policy. Barnett in his paper does not offer enough that is new to overrule those concerns.

Twenty-two fatal accidents are given for 14 C.F.R. Part 121 scheduled passenger operations in the years 1975 to 1986 (*2*,Table5.4). This number excludes accidents involving weather turbulence, sabotage, or a nonoperational event (ramp activities). By further excluding two mid-air collisions and three accidents involving air traffic control or maintenance personnel, 17 fatal accidents are tabulated. A total of 19 fatal accidents between 1977 and 1989 for a subset of the trunkline carriers studied by the authors are given by Neyman and Pearson (*3*,Table5.8). The authors' consider nine fatal accidents for the trunkline carriers in the years 1977 to 1986, and three for the new entrants. Discrepancies of this sort are common in my experience with data on air transportation and may result from different definitions, reporting methods, or inclusion and exclusion criteria.

REVIEWER 2

In his paper, the author begins by declaring that his goal is "to avoid an unnatural deemphasis on [fatal] crashes because of statistical misunderstandings." After a review of his paper, however, it would appear that the author is guilty of an overemphasis on fatal crashes by statistically "stretching" a very small amount of information. Having considerable experience in the analysis and inference of small, rare probability events (traffic accident data and cancer clinical trials), this reviewer feels that too much has been said about too little in the paper and previous articles referred to in this manuscript.

Whereas it is true that one should not uniformly dismiss information based on small sample sizes, by the same token, one should not exaggerate the potential meanings of conjectures based on this information. Such statements as "the overall domestic jet safety . . . would have improved more without the [deregulation] policy shift" based on only three fatal crashes are indeed a "stretch" of statistical inference. That the statistical tests of hypotheses that there is no difference in the safety of established carriers before deregulation and new entrants are rejected at some significance level does not mean that (a) there is, in fact, a true difference in their safety or (b) this difference is caused by deregulation. Two basic flaws are inherent in such conclusions.

- When testing a statistical hypothesis on the basis of one given set of data, the conclusion is simply that we fail to have sufficient evidence to not reject the hypothesis. (Grammatically it would be more appealing to avoid a double negative but this would require the use of the word "accept." By the same token, the result of a given data set never justifies acceptance of a hypothesis, merely failure to reject.). This does not mean that the hypothesis (equality of safety) is false.
- A causal relationship cannot be established by a single study, especially a retrospective, noncohort study (*4*).

By definition, the analyses in this and related manuscripts are based on what is called a case-control, retrospective study in epidemiology. Studies that try to relate the effects of an exposure factor, such as cellular telephones, to rare diseases, such as malignant brain tumors, use this approach and are often guilty of extrapolating more from the data than is justified. In this example, the study is retrospective because it is based on events that occurred before the analysis and is considered a case-control study because the case of new entering flights is being compared with a "control" (established carriers). Although the established carriers are not a control by standard definition, when comparing two groups, one group is termed the "control" in the epidemiological vernacular. At any rate, a common misinterpretation of these results is to interpret a "relative risk" and infer cause and effect. The author has done both in interpreting the safety of the two airline groups. "When both the supposed cause and effect of interest are rare in the general population, the standard retrospective methods often lack sufficient statistical power to evaluate the association of these factors" (*2*). The *Encyclopedia of Statistical Sciences* also states that in such a study design, the rates of the outcomes (fatalities) within groups (existing and new entrants) cannot be estimated with any reliability (*2*).

The conclusions drawn from this study of rare events (fatal plane crashes), which compares two groups on the basis of extremely low occurrences of these events, are equivalent to comparing two cancer treatments and making a decision as to which treatment is best on the basis of a very few subjects. In such cases, information about the few but meaningful subjects should not be ignored but neither should a decisive conclusion be drawn using inferential statistical methods that require large amounts of information. In those situations, case studies should be relied on and expert knowledge used to try to formulate conclusions to benefit the population. And so it must be with airline crashes. Every crash must be studied in detail and general conclusions drawn on the basis of any observable patterns. Criticizing studies that are based on small numbers is not saying that small numbers are not meaningful but that the numerical assessment of the implications of such studies must be combined with good science and not based purely on statistical probabilities. In the words of Neyman,

> [Statistical] tests themselves give no final verdict, but as tools help the worker to form his final decision. . . . What is of chief importance in order that a sound judgement be formed is that the method adopted, its scope and its limitations, should be clearly understood. . . . (*3*)

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AUTHOR'S CLOSURE

I thank the discussants for their thoughtful comments about my paper. Because their remarks concentrated heavily on my airline deregulation work with Higgins "Airline Safety: The Last Decade," I focus my response on that particular data analysis.

Let me begin with some background. It was widely asserted in the late 1980s that, because U.S. air travel was statistically safer after deregulation than before, the policy shift could not have had an adverse effect on passenger safety. But Higgins and I argued that the germane comparison was not between safety levels in the 1980s and those in the 1970s, but between risks in the 1980s and those that would have prevailed at that time if deregulation had not occurred. We performed several calculations to facilitate the latter comparison.

We emphasized those scheduled domestic jet flights from 1979 to 1986 that had resulted in passenger fatalities. We put the accident into two groups: those on which at least half the passengers had died (the disasters) and those on which the majority survived. All events in both categories entered our risk estimates for air travelers; in testing particular patterns for statistical significance, however, we considered only the disasters.

The first reviewer is troubled that we only partitioned fatal events as we did after the fact. In reality, we were following a convention from an earlier paper written before deregulation (*1*,p.1045). Still, the partitioning rule may seem odd: why should a crash that kills 51 percent of the passengers be treated differently from another that kills 49 percent?

Following the pattern of earlier years, nine fatal events from 1979 to 1986 on scheduled U.S. domestic jet flights emerged as heavily polarized between those in which almost no one survived and those in which almost everyone did (Table 3). Five disasters in the table caused more than 99 percent of domestic jet deaths over the 8-year period. As a practical matter, therefore, disaster risk and total risk are almost the same.

With fewer than 5 percent of domestic jet flights from 1979 to 1986, the new entrants suffered 40 percent of the disasters (2 out of 5). The death risk per flight was more than 12 times that of the established carriers. Reviewer 1 suggests that rather than compute an overall statistic, we consider passenger risk in two stages:

1. What is the probability that a randomly chosen flight results in any passenger fatalities?
2. Given that there were such fatalities on a flight, what is the probability that a randomly chosen passenger aboard was killed?

It is suggested that the answer to the second question was roughly 58 percent for the established carriers and 65 percent for the new entrants, corresponding to survival rates of 42 and 35 percent, respectively (Table 3).

These survival rates for the two airline groups are not very far apart. But this similarity does not render the factor-of-12

TABLE 3 Fatalities on Two Groups of Domestic Jet Airlines (1979–1986)

		Airline	Date	Percentage of Passengers Killed
ESTABLISHED CARRIERS:	(1)	American	6/79	100 (%)
	(2)	Pan Am	7/82	100
	(3)	Delta	8/85	83
	(4)	USAir	1/79	5
	(5)	Republic *	1/83	3
	OVERALL AVERAGE			58
NEW ENTRANTS:	(6)	Midwest Express	9/85	100
	(7)	Air Florida	2/82	95
	(8)	World	2/82	1
	OVERALL AVERAGE			65

* Republic Airlines, formed from the merger of Southern, Hughes Airwest, and North Central, subsequently became part of Northwest.

statistic misleading. We must, after all, also consider the reviewer's first question, the answer to which reveals that new entrants were far likelier than other carriers to suffer fatal events. Delving into the reasons for an overall risk disparity is surely sensible; although we must be careful lest the complexity of the inquiry obscure the magnitude of the effect it is trying to explain.

Reviewer 1 thinks we went too far in suggesting that deregulation raised the risk of domestic jet travel by about 60 percent. From 1979 to 1986, the death risk per flight on established U.S. airlines was 1 in 11.8 million. Yet because of the weaker record of the new entrants, the overall risk level for U.S. domestic jet travel was 1 in 7.4 million. This second statistic is 1.6 times (60 percent higher than) the first. Higgins and I acknowledged that the risk multiplier of 1.6 was subject to great instability: the confidence interval for the multiplier ranged from 1.03 to 5.02. But, as a first approximation for the effect of deregulation on death risk, 1.6 is easier to defend than most other candidates.

Reviewer 1 also wonders why we grouped six regional airlines—Aircal, Alaska, Aloha, Hawaiian, PSA, and Southwest—with giants like United and Delta rather than with new entrants much closer to their size. A critical reason was that years before deregulation PSA and Aircal were the main providers of California's massive intercity jet service. The same is true about Southwest in Texas, Alaska Airlines in Alaska, and Aloha and Hawaiian Airlines in Hawaii. To treat such airlines as "children" of deregulation, therefore, would seem historically inaccurate.

Despite qualms, Reviewer 1 concedes that the risk disparity we reported was "likely" of statistical significance and hence that we were justified in calling attention to the disparity. The negative summary judgment of Reviewer 1 of our work appears to reflect the view that, even if the new entrants were less safe than other airlines, one cannot say that deregulation was responsible for the difference. It is true that correlation does not imply causality; in this instance, however, one might consider deregulation a causal factor because without it, the new entrants presumably would not have come into being.

We have always acknowledged the point of Reviewer 2 that one cannot absolutely prove with statistics that new entrant carriers were intrisicially inferior in safety. (We did not, as Reviewer 2 contends, say that air safety improved recently *despite* deregulation; we made the weaker statement that it was *plausible* to interpret the data that way.) We certainly agree that every air crash should be carefully scrutinized on its own. But such scrutiny does not make the analysis of groups of crashes superfluous; patterns that emerge clearly from group study could well go undetected when each crash is studied in isolation.

Reviewer 2 implicitly compares our work to some unspecified small-sample studies about cancer and automobile accidents. I do not doubt that some people have said more than they should have on the basis of small samples (much as we would have done if we had highlighted the factor-of-12 outcome without considering its statistical significance). But the reviewer's argument appears to boil down to guilt by association, which seems especially unfortunate because the point we were stressing was "not that small samples are inevitably useful, [but] that they are not inevitably useless."

Once when the *Washington Post* was accused of printing an inaccurate news report, it offered the succinct response "we stand by our story." Higgins and I respect and thank the reviewers, but, having considered their reservations about our work, we too stand by our story.

REFERENCE

1. Barnett, A., M. Abraham, and V. Schimmel. Airline Safety: Some Empirical Findings. *Management Science*, Vol. 25, No. 11, Nov. 1979.

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