Tilt Rotors and the Port Authority of New York and New Jersey Airport System

Jerome Aroesty, David Rubenson, Geoffrey Gosling
The research described in this report was sponsored by the Port Authority of New York and New Jersey.

ISBN: 0-8330-1110-3

The RAND Publication Series: The Report is the principal publication documenting and transmitting RAND's major research findings and final research results. The RAND Note reports other outputs of sponsored research for general distribution. Publications of RAND do not necessarily reflect the opinions or policies of the sponsors of RAND research.

Published 1991 by RAND
1700 Main Street, P.O. Box 2138, Santa Monica, CA 90407-2138
Tilt Rotors and the Port Authority of New York and New Jersey Airport System

Jerome Aroesty, David Rubenson, Geoffrey Gosling

Prepared for the
Port Authority of New York and New Jersey

RAND
PREFACE

This report represents work done for the Port Authority of New York and New Jersey on the potential impact of the tilt-rotor aircraft on the capacity of the New York metropolitan area airport system. Because the Port Authority operates the three major airports in the New York/New Jersey region, the tilt rotor is of interest because its revolutionary features could greatly expand the capacity of the aviation system. The tilt rotor combines the vertical take-off and landing capability of a helicopter with the range, speed, and comfort of a modern turboprop. These unique features could be used to augment airport capacity in a variety of ways. The project was conducted in RAND's Domestic Research Division, headed by RAND Vice-President Dr. David Lyon.

Dr. Gosling is on the staff of the Institute for Transportation Studies, University of California, and is a consultant to RAND.
SUMMARY

The development of the V-22 tilt-rotor aircraft and demonstration flights of the XV-15 have captured the imagination of the technical, military, and political communities. With the vertical flight ability of a helicopter and the speed, size, range, and level-flight performance of a turboprop, the tilt rotor culminates years of vertical/short take-off and landing (VSTOL) development.

Tilt-rotor technology is also perceived as a potential remedy for the problem of increasing capacity at congested metropolitan airports. Given the enormous barriers to building new airports and runways, airport operators and the Federal Aviation Administration (FAA) are sensitive to approaches that could augment capacity at existing airports or divert travelers to smaller regional “vertiports.” As a result, a number of studies are being performed around the nation to determine whether and how civil tilt-rotor aircraft could improve the performance of the national air transportation system.

This report documents a study that evaluated the possible role of the tilt rotor in alleviating airport capacity problems in the region served by the Port Authority of New York and New Jersey. Because a civil derivative of the V-22 could carry between 31 and 39 commercial passengers up to a distance of 600 n mi, it would be analogous to the turboprop aircraft used by commuter airlines to bring passengers to New York City from cities such as Albany, Philadelphia, Providence, Baltimore, and Hartford. Commuter aircraft use the same runways as large jets, thus reducing the passenger capacity of the runways. Tilt-rotor craft could increase airport capacity by replacing commuter aircraft at the Port Authority’s three major airports—John F. Kennedy, Newark, and La Guardia. Because tilt rotors do not require use of a runway, diversion of commuter passengers to tilt rotors would partially free the congested runways for larger aircraft. The analysis assumes that the tilt rotor could operate virtually independently of the large jets in other critical ways.

For purposes of analysis, we have considered all short-haul markets within 350 n mi of New York as primary candidates for tilt-rotor service. Aggregate passenger levels to and from New York are forecast at 22 million for 1995, rising to 30 million in 2005. This compares to a level of 16 million in 1987. Approximately 40 percent of the short-haul passengers travel to or from Washington, D.C., and Boston. Making optimistic but plausible assumptions about tilt-rotor performance costs and market behavior, we forecast that scheduled commuter operations of a 31-passenger craft operating at a 65 percent load factor could support a baseline of 42 average tilt-rotor round trips per day if the service were available in 1995.

A second way the tilt rotor could expand the capacity of the airport system is by operating from a network of regional vertiports scattered throughout the New York/New Jersey region. A major obstacle to constructing new airports is the large land area needed for runways; a series of vertiports could allow passengers access to air travel without traveling to one of the three major airports. This would reduce passenger ground travel time and divert passengers from the already overcrowded airports. Capacity would be increased both on the ground and in the air. A potential problem would be the willingness of communities to accept a local vertiport. For a single midtown Manhattan vertiport, we forecast 52 tilt-rotor round trip operations per day in 1995. Most of the operations would provide service to and from Washington and Boston airports. For a fully dispersed regional vertiport system, we forecast 159 daily round trips in 1995 if the system were fully operational throughout the northeast corridor.
A third way, intrinsically less attractive than the first two from the perspective of alleviating congestion, is for tilt rotors to operate in a shuttle mode between New York airports and high-volume destinations such as Washington, D.C., and Boston. This mode may eventually be attractive to airlines who view these large markets as offering the ability to support tilt-rotor service even at low market share. The key issues are acceptance by passengers and whether tilt rotors are viewed as inferior to larger aircraft. For airport operators, shuttle service of this type would be attractive only if the tilt rotor could offer travel time advantage and air and ground space utilization benefits superior to those of existing jet shuttle service. Such benefits might follow from tilt-rotor operations that were virtually independent of fixed-wing operations. The penalty is the substitution of four or five tilt-rotor flights for one jet shuttle and the resulting effect on the airspace system. If passengers become indifferent to the intrinsic differences in size, amenities, and service quality between tilt rotors and larger aircraft, then we forecast approximately 50 tilt-rotor round trips between the two cities and the New York airports. If passenger attitudes toward smaller aircraft remain as they are, our forecasts suggest virtually no tilt-rotor penetration.

The tilt rotor offers potential benefits, but several issues must be confronted before defining its ultimate impact on the airport system and the steps that must be taken to realize those benefits. The tilt rotor is likely to be more expensive than fixed-wing aircraft. The willingness of passengers and carriers to incur higher costs must be compared with the perceived benefits offered by the vehicle. If the tilt rotor is to increase the capacity of existing airports by diverting small commuter aircraft from the runways, then it must also be able to traverse the nearby airspace without interfering with fixed-wing traffic. It does little good to free runways if air space congestion is increased. Moreover, public perceptions of the vehicle are highly uncertain. There are few successful regularly scheduled helicopter services, and passenger association of the tilt rotor with helicopters could have an adverse effect on its market potential.

Closely related to all of these factors is tilt-rotor technology. If the benefits are great enough, if the public is confident enough, and if existing travel operations are becoming unusable, then an early civil version of the V-22 may be desirable. However, it is also possible that markets may require a larger, quieter, and less expensive vehicle, and will not accept a near-term variant of the available technology. In this case, the emphasis should be on technology development rather than on premature commercialization or infrastructure development.

Our purpose, as we conducted the study, was to analytically assess the costs and benefits of the civil tilt rotor, to evaluate its potential for increasing the capacity of the New York airport system, and to judge the relative importance of markets, technology, and infrastructure development. A variety of techniques were employed to investigate the feasibility of using these vehicles at existing airports, potential passenger attitudes toward the vehicle, the required infrastructure, the value that passengers assign to reduced ground travel time, the demographics of commuter travelers, and several other related issues. These factors were then folded into a demand forecast methodology to estimate the potential tilt-rotor market in the New York area. The methodology employed a classic modal share model using demand parameters estimated from a number of sources. The model guided our judgments about future demand and destination cities that might be suitable candidates for service.

Focus groups and surveys were part of our exploration of the potential of this technology for alleviating airport congestion in the New York region. Although diverse techniques were employed, the results did not vary. The unique features of the tilt rotor offer a significant opportunity to reduce airport congestion, but realizing such benefits may take many years. The estimated costs of the tilt rotor, doubts about a vehicle that many associate with
helicopters, and the reluctance of potential operators and acquirers to step forward imply that a minimally modified civil version of the V-22 is not likely to gain significant market penetration. Our baseline demand forecasts—based on an average value of $25 for each hour of travel time saving—were not very encouraging, even using moderately optimistic parameters for tilt-rotor performance. The forecasts would be more promising if a large number of potential travelers valued travel time at higher dollar levels than the less than $25/hr revealed by our research. Doubling the value of travel time to $50 per hour virtually doubled the aggregate number of tilt-rotor operations to meet demand. The problem of airport congestion is severe, but probably not yet severe enough to motivate the private sector to pursue this technology in the face of market and technological uncertainties. Until such uncertainties are narrowed, it is not possible to properly assess the costs and benefits of subsidies or other nonmarket mechanisms to encourage tilt-rotor utilization.

There is little doubt that tilt-rotor technology is promising, and that the infrastructure necessary to support a system could be feasible (although La Guardia poses difficult problems). Although FAA requirements for communications, navigation, and surveillance systems or operating and air traffic control procedures to facilitate visual and instrument flight operations have not yet been promulgated, our preliminary analysis suggests that tilt rotors could operate virtually independently of fixed-wing traffic in the New York Terminal Control Area.

The crucial issues from the point of view of demand forecasts are tilt-rotor operating costs, the extent of consumer aversion to tilt rotors because of their association with helicopters, their smaller size compared to jet aircraft, and the ability of a tilt-rotor system to provide efficient, safe, and reliable service at significant time savings. Another important question, not generally considered, is the question of who would operate tilt rotors. Would they be operated by certificated carriers, by commuter airlines, or by other entities not yet determined? Both the character of the operator and the nature of the total operating environment would determine the strategy to be adopted by both fixed-wing and tilt-rotor operators. Commuter operators are not now interested in providing service that diverts them from their main objective—to provide connecting service that enhances fare revenues for their associated major carriers. A major restructuring of the air transportation industry would be necessary for them, or major carrier partners and owners, to initiate city center-to-city center service. Furthermore, the estimated maintenance costs and reliability of tilt-rotor aircraft may be too close to that of rotary-wing equipment for operators of conventional airplanes to consider tilt-rotors as suitable substitutes for larger, less costly, and more reliable modern turboprops. Tilt-rotor technology and operations must be measured against a fixed-wing rather than rotary-wing standard of reference.

We therefore conclude that an additional cycle of technology evolution bringing reduced costs, increased reliability, and increased public confidence will be required before airport operators can seriously consider the vehicle as an option for reducing congestion. Such improvements will be required to make investment in the vehicle appear to be an attractive business venture. At this time, the primary policy initiatives for stimulating these improvements do not lie with airport operators such as the Port Authority of New York and New Jersey, but with federal agencies (e.g., the FAA, the National Aeronautics and Space Administration, and the Department of Defense) who must decide whether and how they can continue to promote this potentially attractive technology. The role of the FAA is particularly significant in terms of developing standards, criteria and the systems that enable tilt-rotor aircraft to realize their optimal potential.
Initiatives also lie with the tilt-rotor manufacturers. They must judge whether adequate promise exists to justify the major resource commitments needed to accelerate development to the point where diffusion of civil tilt-rotor technology could markedly increase the capacity of the air transportation system.
# CONTENTS

PREFACE ........................................................................ iii

SUMMARY ................................................................. v

FIGURES ................................................................. xi

TABLES ................................................................. xiii

Section

I. INTRODUCTION ......................................................... 1
   Commercial Air Traffic in the New York City Metropolitan Area .......... 1
   Options for Expansion ................................................. 1
   The Tilt Rotor ......................................................... 4
   Research Issues ....................................................... 6
   Organization .......................................................... 7

II. AIR TRAFFIC CONTROL AND OPERATIONS AT THE
    THREE AIRPORTS .................................................. 8
    The New York/New Jersey Terminal Control Area ....................... 9
    La Guardia .......................................................... 9
    Newark Airport ..................................................... 19
    John F. Kennedy International Airport .................................. 24
    Summary of the Air Traffic Control Problem .............................. 28
    Advanced Automation and a Future Tilt-rotor System ................. 32
    Needed Measurements ............................................... 34

III. AIRPORT TILT-ROTOR CAPACITY AND INFRASTRUCTURE
    REQUIREMENTS .................................................... 35
    Operations at Free-standing Vertiports .................................... 35
    La Guardia .......................................................... 37
    Newark and Kennedy ............................................... 41

IV. EVALUATION OF TILT-ROTOR FOCUS GROUPS .......... 44
    Purpose of the Focus Groups .......................................... 44
    Structure of the Focus Groups ....................................... 44
    Reactions to Existing Transportation Services ......................... 45
    Reactions to the Tilt-rotor Concept ................................... 49
    Implications for Developing Tilt-rotor Markets .......................... 52

V. THE ALBANY PASSENGER AND CORPORATE SURVEYS .... 54
   Rationale for the Passenger Survey ....................................... 54
   Data Analysis ................................................................ 56
   Implications .................................................................. 62
   The Corporate Survey .................................................. 64

VI. MARKET DEMAND ANALYSIS: APPROACH TO THE ANALYSIS . 68
   Background .................................................................. 68
   Issues and Assumptions ................................................ 68
   Tilt-rotor Service at Regional Vertiports ................................ 70
   Slot Assignment ....................................................... 71
Analysis Approach ......................................................... 71
Potential for Travel Time Reduction ................................. 72

VII. MARKET DEMAND ANALYSIS: POTENTIAL MARKETS .......... 74

VIII. MARKET DEMAND ANALYSIS: MODELS, PARAMETERS, AND INTERPRETATION ........................................ 77
Models ........................................................................ 77
Parameters ................................................................... 79
Scenario Analysis .......................................................... 92

IX. MARKET DEMAND ANALYSIS: FORECASTS .................... 93
Screening Assumptions ................................................... 93
Market Share Analysis Results .......................................... 95

X. CONCLUSIONS .......................................................... 104
The Tilt Rotor at the Three Airports ................................. 105
Regional Vertiports ....................................................... 107
Potential Governmental Actions ....................................... 108

Appendix
A. INTEGRATION OF THE TILT ROTOR INTO THE AIR TRAFFIC
   CONTROL SYSTEM .................................................. 111
B. REVIEW OF PREVIOUS MODELS .................................. 119

REFERENCES ............................................................... 129
<table>
<thead>
<tr>
<th>FIGURES</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Typical traffic distribution at La Guardia</td>
<td>2</td>
</tr>
<tr>
<td>2. Typical traffic distribution at John F. Kennedy International</td>
<td>3</td>
</tr>
<tr>
<td>3. Typical traffic distribution at Newark</td>
<td>3</td>
</tr>
<tr>
<td>4. The XV-15 in transition</td>
<td>5</td>
</tr>
<tr>
<td>5. Schematic of the CTR-22C</td>
<td>5</td>
</tr>
<tr>
<td>6. The New York Terminal Control Area</td>
<td>10</td>
</tr>
<tr>
<td>7. La Guardia airport</td>
<td>11</td>
</tr>
<tr>
<td>8. La Guardia airport—potential sites</td>
<td>12</td>
</tr>
<tr>
<td>9. ILS approach to runway 22</td>
<td>14</td>
</tr>
<tr>
<td>10. Potential altitude profile</td>
<td>16</td>
</tr>
<tr>
<td>11. Existing helicopter routes</td>
<td>18</td>
</tr>
<tr>
<td>12. Potential tilt-rotor sites</td>
<td>20</td>
</tr>
<tr>
<td>13. Runway configuration</td>
<td>21</td>
</tr>
<tr>
<td>14. Tilt-rotor and fixed-wing approaches</td>
<td>22</td>
</tr>
<tr>
<td>15. Simultaneous fixed-wing and tilt-rotor approaches</td>
<td>24</td>
</tr>
<tr>
<td>16. Layout of Kennedy airport</td>
<td>25</td>
</tr>
<tr>
<td>17. Potential landing areas at JFK International</td>
<td>27</td>
</tr>
<tr>
<td>18. Tilt-rotor and fixed-wing operations on 13/31</td>
<td>29</td>
</tr>
<tr>
<td>19. Tilt-rotor operations in a future congested scenario</td>
<td>30</td>
</tr>
<tr>
<td>20. A representative city center vertiport</td>
<td>36</td>
</tr>
<tr>
<td>21. The employee parking area at La Guardia</td>
<td>38</td>
</tr>
<tr>
<td>22. Comparison of vertiport and parking area</td>
<td>39</td>
</tr>
<tr>
<td>23. Comparison of vertiport and parking area with 45 degree rotation</td>
<td>40</td>
</tr>
<tr>
<td>24. Landing pads in the parking area</td>
<td>41</td>
</tr>
<tr>
<td>25. VTOL tilt-rotor landing area at JFK</td>
<td>42</td>
</tr>
<tr>
<td>26. VTOL tilt-rotor landing area at Newark</td>
<td>43</td>
</tr>
<tr>
<td>27. A RAND Corporation study of new aircraft technology</td>
<td>46</td>
</tr>
<tr>
<td>28. Photograph of a tilt rotor</td>
<td>47</td>
</tr>
<tr>
<td>29. Survey presented to Albany passengers</td>
<td>55</td>
</tr>
<tr>
<td>30. Albany/New York round trips during the past 12 months</td>
<td>56</td>
</tr>
<tr>
<td>31. Mode of transportation for trips during the previous 12 months</td>
<td>57</td>
</tr>
<tr>
<td>32. Distribution of flight times</td>
<td>58</td>
</tr>
<tr>
<td>33. Distribution of final destinations</td>
<td>59</td>
</tr>
<tr>
<td>34. Ground transportation mode</td>
<td>60</td>
</tr>
<tr>
<td>35. Ground travel time</td>
<td>60</td>
</tr>
<tr>
<td>36. Ground travel costs</td>
<td>61</td>
</tr>
<tr>
<td>37. Willingness to pay for vertiport service</td>
<td>62</td>
</tr>
<tr>
<td>38. Survey on executive and middle management travel policies</td>
<td>65</td>
</tr>
<tr>
<td>39. Survey cover letter</td>
<td>67</td>
</tr>
<tr>
<td>40. Average delay per air carrier operation</td>
<td>91</td>
</tr>
<tr>
<td>41. Tilt-rotor market share vs. fare premium</td>
<td>97</td>
</tr>
<tr>
<td>B.1. Comparison of utility formulations</td>
<td>120</td>
</tr>
<tr>
<td>B.2. Market share vs. cost difference</td>
<td>122</td>
</tr>
<tr>
<td>B.3. Market share vs. time difference</td>
<td>122</td>
</tr>
<tr>
<td>B.4. Effect of aircraft size on QSI</td>
<td>126</td>
</tr>
</tbody>
</table>
TABLES

1. Reactions to hypothetical price hikes for air segment ........................................... 61
2. Forecasts of aggregate to and from New York passenger traffic (1000s/year) .......... 75
3. Cities 350 to 500 n mi from New York with passenger volume > 100,000 in 1995 ...... 75
4. Cities < 350 n mi from New York with passenger volume > 100,000 in 1995 ............ 76
5. Aircraft delay trends at the NY/NJ airports .......................................................... 90
6. Delay reduction from potential capacity enhancement measures ............................ 92
9. Scenario c: optimally dispersed vertiports in Port Authority area (1995 forecast) ..... 103
B.1. Choice model parameter comparison ................................................................... 119
B.2. Comparative implied values .................................................................................. 123
B.3. Air travel times and fares: 1987 .......................................................................... 127
I. INTRODUCTION

COMMERCIAL AIR TRAFFIC IN THE NEW YORK CITY METROPOLITAN AREA

The New York City metropolitan area is the busiest commercial air traffic region in the world. With more than 74 million commercial passengers in 1989, the region is faced with a continuing airport capacity problem.¹ Commercial air transport services are provided at three major airports: La Guardia (LGA), Newark International (EWR), and John F. Kennedy (JFK). La Guardia is closest to the Manhattan business district and the high population density areas of New York City. This airport is primarily used for flights with destinations in the eastern half of the United States. JFK is far from the city center and is principally used for international and cross-country flights, although there are a substantial number of shorter flights providing connection service. Newark falls between these two categories in both range of flights and distance to the city,² although it is gaining in terms of international service and accessibility to downtown Manhattan.

With today's traffic levels, congestion is already a source of inconvenience for passengers and airport operators. Simply getting to the airport is a major problem. New York's highways are often congested and none of the airports is connected by rail link. Once near the airport, passengers must travel through an even more heavily congested area to access the terminals. Although airside delays are not a severe problem during good weather, backlogs can develop during conditions of poor visibility or inclement weather. During the peak traffic hours, the runways at all three airports operate at or near peak capacity and it is difficult to meet the demands for flights at this time. These problems are expected to become more severe as the number of passengers increases in the coming years.

OPTIONS FOR EXPANSION

Meeting the growing demand for air travel and facilitating access to airports are ongoing tasks for the Federal Aviation Authority (FAA) and the operator of New York's airports, the Port Authority of New York and New Jersey (PANYNJ). The Port Authority has examined many potential solutions, but all have limited potential. One obvious solution is to build additional airports. However, the population density of the New York region, coupled with the difficulties in meeting environmental and community standards, makes this option unrealistic. Some operations have already begun at Stewart Field in Orange County, some 70 miles to the north of New York City. These operations could deflect 10–15 percent of the traffic from the major airports—primarily those passengers with origins or final destinations north of New

¹Monthly reports of New York region airport activities are published by the Port Authority's Aviation Department of Marketing and Economics. In 1989 there were 959,000 commercial movements, consisting of 603,000 domestic airline movements, 146,000 international airline movements, 193,000 scheduled commuter movements, and 17,000 air taxi movements. In terms of annual revenue passengers, these movements involved 74.4 million passengers (49.7 million domestic airline passengers, 21.9 million international airline passengers, and 2.74 million scheduled commuter passengers). Thus, scheduled commuter service accounted for 20 percent of commercial airplane movements at all three airports but for only 3.7 percent of revenue passenger traffic.
²Annual revenue passenger volume in 1989 was 30.3 million at JFK, 23.1 million at La Guardia, and 20.9 million at Newark.
York City. However, it is almost impossible to envision a new airport significantly closer to the New York metropolitan area.

Expansion of the three existing airports is ongoing, but can have only limited effects on the capacity of the system. Groundside access is being improved, terminals are being redesigned, and gate capacity is being increased, but these kinds of expansion are limited by the available land. Land availability also prohibits the most important option for increasing airport capacity, new runways. Runways and the nearby airspace represent bottlenecks in the system. Without new runways, the capacity of the system is inherently limited.

One possibility for increasing capacity without new runways is to even out the flow of traffic over the business day. Reducing the number of flights at the peak hours of the day would achieve a more even traffic pattern distribution. Figures 1–3 show typical traffic distributions at the three New York area airports and indicate some of the difficulties in this approach. As shown in Fig. 1, the traffic density at La Guardia is roughly constant during the day, with little opportunity for increased efficiency through smoothing. JFK has a sharply peaked distribution, but flexibility is curtailed by flight curfews at European airports, which prevent earlier departures. Finally, it should be noted that demand peaks are a function of passenger preferences to fly at specific times. A forced smoothing of the distribution would represent a reduction in service. Although greater throughput could be achieved, it would be at the expense of the traveling public. If throughput problems are not addressed, such actions

---

Fig. 1—Typical traffic distribution at La Guardia

---

Data for La Guardia and Newark are based on summer 1989 schedules, data for JFK on summer 1988 schedules.
Fig. 2—Typical traffic distribution at John F. Kennedy International

Fig. 3—Typical traffic distribution at Newark
may be forced upon airport operators. However, the current goal is to increase service in a manner consistent with passenger preferences.

Perhaps the most encouraging factors involve trends in markets and technology. As demand for service has increased, there has been movement toward the use of larger aircraft. Since smaller aircraft occupy a disproportionate share of air and runway space on a per-passenger basis, larger aircraft present a more efficient use of runways and airspace assets. Advances in air traffic control (ATC) technology will also allow for safer and more efficient use of the airspace. Nonetheless, finite runway area will restrict the utility of such measures, and without additional runways, there will be insufficient future capacity. What expansion is achieved will exacerbate the problem by increasing the demand to access the airport.

THE TILT ROTOR

The Vehicle

A revolutionary approach to expanding both air and nearby ground capacity may be represented by the V-22 Osprey tilt-rotor aircraft being developed by Bell-Boeing for the United States Marines. The V-22 is a fixed-wing aircraft designed to airlift 24 Marines to a range of approximately 600 miles. It contains the unique feature of rotors that pivot, allowing the vehicle to lift and land in a helicopter mode, while normally traveling in a conventional fixed-wing mode. The V-22 thus combines the speed, comfort, and fuel efficiency of modern turboprop aircraft with the vertical lift capability of a helicopter.

The tilt-rotor vehicle has been described in numerous research reports, journals, and newspapers. The National Aeronautics and Space Administration (NASA) has been test flying a small prototype, the XV-15, for more than 10 years, and the V-22 Osprey troop transport is now in flight testing. A picture of the XV-15 in transition from the helicopter to the fixed-wing mode is shown in Fig. 4.

The civil tilt rotor considered in the NASA/FAA study was required to have a 600 n mi range with vertical take-off and an 800 n mi range in a STOL (short take-off and landing) mode. The difference is indicative of the fuel penalty for the pure vertical mode. The NASA study indicated that a minimum changed V-22 could carry up to 31 passengers in a civil mode. Other versions investigated in the study carry up to 75 passengers. The CTR-22C, used in the market demand analysis presented later in this report, had a design goal of carrying 39 passengers and incorporated a new pressurized fuselage, but did not require engine growth. A sketch of the CTR-22C is shown in Fig. 5. The propulsion system for the 75-seat CTR-7500 was not analyzed in the NASA study.

Potential Impact on Airside and Groundside Capacity

The potential commercialization of tilt-rotor technology could have a significant impact on airport capacity in the New York region. Since the first civil tilt rotors are likely to be small (31 to 39 passengers), and limited in range to about 600 miles, they are analogous to today's turboprop aircraft used to service nearby commuter markets such as Albany, Hartford, Chicago, and Boston.
Fig. 4—The XV-15 in transition

CTR-22C

Fig. 5—Schematic of the CTR-22C
Providence, and other mid-size cities. These small aircraft account for some 20 percent of the scheduled aircraft movements in the New York City region, but carry only a few percent of the passenger traffic. If these aircraft could be replaced by tilt rotors, they could make a significant impact on airport capacity. During peak hours, when the runways are congested, tilt rotors serving commuter cities could land at alternative areas of the airport without requiring a runway. Airport capacity would be increased by diverting commuter operations from the runway onto a much smaller and compact tilt-rotor landing pad. The vacancies on the runways could then be used by larger aircraft.

An alternative use for the tilt rotor would be to offer passengers the opportunity of not having to go to the airport. A major obstacle preventing the construction of new airports is the large area of land required for runways. The tilt rotor's vertical landing and take-off capability might allow for the construction of "vertiports" at key areas around the city. Such vertiports would be significantly smaller than major airports. Instead of traveling to a major airport, passengers might be able to access a conveniently located vertiport. New vertiports would not only increase the capacity of the air transport system, but they could divert ground traffic from the major airports, hence adding groundside capacity to the overall system. If conveniently located, such vertiports would also save travelers ground travel time.

**RESEARCH ISSUES**

The operator of the New York airports, The Port Authority of New York and New Jersey, has long recognized the potential benefits of tilt-rotor technology as a method of increasing system capacity and in fact commissioned a study of the tilt rotor's applicability in the New York region.\(^6\) That study concluded that regional vertiports offered substantial potential to divert short-haul traffic from the major airports, thereby increasing the airside capacity of the system and alleviating groundside congestion near the airport.

Although the Hoyle-Tanner study highlighted the potential advantages of the tilt rotor, the scope of the study did not allow detailed investigation of the issues that will ultimately determine the utility of the tilt rotor in the New York City region. The study did not consider its use at existing airports to displace small commuter aircraft. More detailed analysis is required before we can determine the market appeal of tilt rotors operating at vertiports. Although such vertiports may offer passengers and airport operators significant advantages, the tilt rotor operating costs are likely to be higher than those of conventional fixed-wing aircraft. Furthermore, there has been a traditional market resistance to helicopters.\(^7\) Since the tilt rotor shares certain features of the helicopter, it is possible that it will inherit some passenger resistance. A central objective of our study is to compare the estimated benefits of the tilt rotor with its costs and arrive at a realistic assessment of the tilt rotor's market potential and viability as a vehicle for a transportation enterprise. *Realistic, in this case, implies a willingness, lacking until now, to consider both advantages and drawbacks.*

In addition to market factors, issues related to tilt-rotor technology and airport infrastructure will also affect the viability of the tilt rotor. If the tilt rotor is used to expand the capacity of existing airports, there must be areas available for landing and take-off and the vehicle must be able to move through the close-in airspace in a manner that is nearly independent of the fixed-wing air traffic. Terminals and access might also have to be provided at the

---


\(^7\)Some possible reasons for this resistance are presented in Sec. IV.
airports. If the tilt rotor is to be used as part of a system of regional vertiports, land must be found for these vertiports. Although such facilities require far less land than is needed for new airports, the congestion in the New York area suggests that even smaller facilities may be difficult to site and to gain community approval.

Perhaps even more critical is the interaction among markets, technology, and infrastructure. Markets may well depend on the quality and level of service that can be provided and by the infrastructure. The amenities and comfort of the vehicle can be expected to interact with the market demand. The purpose of this study is to evaluate these interactions to gain a better understanding of the tilt rotor's potential to expand the capacity of the New York air transportation system.

ORGANIZATION

Two major issues are considered in this report: (1) the feasibility and appeal of using tilt rotors to displace commuter aircraft at the three major New York area airports, and (2) the potential for operating tilt rotors from a system of regional vertiports as a means of diverting traffic from the airports and saving passengers ground transit time.

Operation at the major airports is considered in Secs. II and III. Areas for operating the tilt rotor are identified in Sec. II as bases for moving the tilt rotor through the nearby airspace independent of fixed-wing traffic. The infrastructure required at the airports for such operations is discussed in Sec. III. These two sections address only feasibility and do not consider the desirability from either a passenger or operator perspective.

The market analysis, and the related issues of ticket prices, vehicle costs, regional vertiport siting, and passenger demographics are presented in Secs. IV–IX. Section IV reports the results of passenger focus group evaluations conducted to gain a better understanding of passenger preferences, including attitudes toward the tilt rotor and toward the value of saving time. Section V relates the results of a passenger and corporate survey intended to gain different perspectives on similar issues. The qualitative conclusions gained from these market analysis techniques are then used to refine and support the passenger demand forecasting described in Secs. VI–IX. Section VI introduces demand forecasting and Sec. VII presents estimates of the total potential short-haul markets from the New York City region. A detailed review of forecasting models and our financial, economic, and technical assumptions are given in Sec. VIII. Information gained from the focus groups and surveys helped form the basis for some of our assumptions. These assumptions are then used to guide the tilt-rotor demand estimates for both an airport- and a vertiport-based system presented in Sec. IX. The conclusions are summarized in Sec. X, along with a set of policy recommendations.
II. AIR TRAFFIC CONTROL AND OPERATIONS AT THE THREE AIRPORTS

The possibility of increasing capacity at the three existing airports in the New York area through the addition of tilt-rotor operations is dependent on making such operations independent of fixed-wing traffic. Tilt rotors could be integrated into the existing air traffic system, but they would occupy the same airspace as other aircraft. The higher tilt-rotor operating costs imply that operators would have little interest in such operations. However, if tilt rotors could operate independently of fixed-wing traffic, airport capacity could be increased and substantial benefits for the air transportation system would be realized. A portion of these societal benefits might then be passed on to tilt-rotor operators to ensure that tilt-rotor operations would be financially attractive.

Tilt-rotor operations at existing airports therefore depend on workable procedures that allow operations to be independent of fixed-wing traffic. Independence is, of course, a relative term. At a minimum, tilt rotors will increase the requirements for related ground capacity, including access, parking, and terminal throughput. Independence in the air will also be limited, and tilt-rotor operations will have some interaction with fixed-wing operations. However, if tilt rotors can operate without using the overcrowded runways or congested approach paths under instrument landing rules (IFR), then tilt rotors will not affect the existing air choke points. Capacity could be increased, although less sensitive parts of the system might experience increased congestion.

The FAA is not likely to promulgate tilt-rotor transportation criteria and operating and air traffic control procedures for a number of years, despite plans to permit early FAA participation in the DoD V-22 flight test program. It is likely that the critical issue of the permitted range of descent glideslope angles will require extensive FAA-specific flight tests and simulator data. Furthermore, the requirements for communications, navigation, and surveillance systems to properly integrate tilt-rotor visual and instrument operations into the National Airspace System with minimal impact on fixed-wing operations have not yet been formulated. The importance of these issues cannot be overstated, particularly the need for provisional or interim guidance that will enable manufacturers, planners, potential operators, and others to be confident that the tilt rotors' unique flight characteristics will be realized in practice. Appendix A indicates, at a conceptual level, how the tilt rotor could be integrated into the future Air Traffic Control system. Given this uncertainty, this section proposes a set of possible procedures and technical requirements that will allow tilt rotors to avoid runways and IFR approach paths. Since specific air traffic criteria and instrument procedures for tilt rotors have yet to be established, the analysis cannot be regarded as a working plan for conducting tilt-rotor operations. Instead, the purpose is to show what is required for such operations. Requirements involve the potential use of airport land for tilt-rotor landing, take-off, and passenger access, separation criteria, and new air traffic control technology. The ultimate feasibility of independent or nearly independent operations still remains to be determined, based on the requirements posed here.

---

1By independence we ideally mean that tilt-rotor traffic could be added to the system without affecting the fixed-wing capacity of the system.
The procedures, criteria, and technologies identified in this analysis pertain to the air traffic control problem at the airport and out to the region where sequencing for final approach begins, which can be as distant as 50 miles from the airport. Tilt rotors beyond this point will operate as fixed-wing aircraft and contribute to en route congestion. We assume, however, that en route congestion is a less severe problem and that it is being addressed elsewhere. In their fixed-wing mode, tilt rotors present no unique problems or opportunities.

We note that even with a workable set of procedures, independent operation does not imply that tilt-rotor operations can lead to arbitrary increases in air capacity. The availability of space for landing sites and tilt-rotor parking will limit the number of operations that can be conducted. This and other airport-specific factors will be evaluated in the following section, where the impact of tilt rotors on airport capacity will be quantified.

THE NEW YORK/NEW JERSEY TERMINAL CONTROL AREA

The airspace above the New York City region is perhaps the most complex and heavily trafficked in the country. Within the New York terminal airspace are 25 small airports, three mid-sized airports (Teterboro, White Plains, and Islip), and three large airports: La Guardia, Newark, and Kennedy. A diagram of the New York Terminal Control Area (TCA) is shown in Fig. 6.

Because of the density of airports in the region, flow patterns are strictly maintained and coordinated among the three major airports. Tilt rotors will have to remain in this flow long enough to maintain these patterns, and then make a distinct final approach that provides separation from the choke points in the system. This approach would maintain the long-established flow patterns until the point where the system is capacity limited. Procedures and technical requirements for achieving this at each airport are discussed in the following sections.

LA GUARDIA

Location of Tilt-rotor Landing and Take-off

Of the three airports, La Guardia is the most tightly constrained by the parameters that determine air capacity.\(^2\) The runways operate at near peak capacity, land is scarce, and the air traffic environment is highly congested. The entire airport covers only about 600 acres and yet supports over 20 million passengers per year. Increasing the proportion of wide-body operations would increase this number by over one-third during the next decade. A diagram of La Guardia airport is shown in Fig. 7.

As shown in Fig. 7, La Guardia has two crossing runways that operate simultaneously but dependently. A normal operating sequence might consist of departures on runway 13 and landings on runway 22, although weather conditions may warrant departures on runway 31. Under adverse weather conditions, both landing and take-off might occur on runway 4, implying a significantly reduced fixed-wing capacity and substantial delays. Aircraft park in the main terminal area, and at the time this report was written, the Marine terminal was being used by Pan American shuttle operations.

\(^2\)At present, La Guardia is slot-limited by the "high density rule" to no more than 48 air carrier operations, 14 commuter operations, and 6 operations by others per hour; JFK is slot-limited from 3:00 p.m. to 7:59 p.m. Slot limitations at Newark were suspended in 1984. In terms of arrivals, current best IFR capacities are 26 at LGA, 36 at JFK, and 26 at EWR, with new procedures being considered to increase these levels over time. The FAA suggests, for example, that IFR arrivals could reach 35 per hour with dependent converging approach procedures.
The limited physical space at La Guardia constrains options for conducting tilt-rotor operations at the airport. Examination of the map shows few possibilities for siting of tilt-rotor landing and take-off pads, gates, or terminals. In the past, helicopters have been brought across the runway and landed in the area between the maintenance hangars and the taxiways. Such a helicopter landing pad is shown by location 1 in Fig. 8. The approach is from the top or left side of the page over the runways.

The area identified as location 1 is on a long-term lease to American Airlines. The helicopter traffic previously brought into this area was infrequent and did not constitute regularly scheduled service. The helicopters would have to wait for a break in the runway traffic, which was already tightly constrained by the need to coordinate simultaneous operations on the crossing runways. Regularly scheduled tilt-rotor service going across the runway would require additional coordination, and is likely to result in delays for tilt-rotor passengers and significantly increased complexity for air controllers. For these reasons, it is almost essential that the tilt-rotor landing and take-off area be on the opposite side of the runways from the terminals.

There are several potential locations on the opposite side of the runways; however, each currently serves an existing function. La Guardia does have a STOL runway (location 2) that
Fig. 7—La Guardia airport
is used for overflow parking of aircraft and taxiing rather than STOL operations. The far side of the STOL runway (away from the terminals) might serve as a potential landing and take-off site, however, it is not uncommon for this area to be used for overflow parking of fixed-wing aircraft. The Marine terminal area (location 3) is typically filled with parked and taxiing Pan American jets. The existing space is used for police emergency helicopters, with the area being sealed off for VIP arrivals. Area 4, behind the Marine terminal, is used for airport fuel storage, maintenance, a U.S. post office, and other functions.

The most attractive site for tilt-rotor operations is the existing employee parking shown by location 5 on Fig 8. Current plans call for the employee parking to be moved to location 6. Given La Guardia's small size, this area will undoubtedly be desired for more extensive parking of aircraft in overflow situations. However, there are no firm plans for the area, and it is probably the only unclaimed piece of real estate at La Guardia.

A final option is, of course, to build a tilt-rotor platform onto the bay, as shown by location 7 in Fig. 8. Such an option would allow the most operations, but would undoubtedly require an extensive and lengthy environmental impact procedure. We therefore assume that initial tilt-rotor operations will be conducted at the existing employee parking area. As will be discussed in the following section, space limitations imply limits on tilt-rotor operations. Hence, we view expansion into the bay as a longer term option to be considered after operation in the parking area has proven to be technically and financially viable.

Avoiding the Runways and Instrument Landing System (ILS) Approach Paths

Helicopters routinely move through the highly congested airspace of the New York terminal control area by operating under visual flight rules (VFR) or special VFR conditions and by flying on routes beneath the TCA floor. As helicopters approach La Guardia, they may be asked to hold their position until there is an opening in the airspace. Under instrument landing conditions, helicopters enter the ILS approach path and contribute to the congestion at La Guardia in a manner similar to additional fixed-wing traffic.

Although VFR and ILS procedures allow for efficient helicopter operations near the airport, they are unlikely to be adequate for a regularly scheduled tilt-rotor service. We assume that a commercial tilt rotor will have to offer the same all-weather capabilities as fixed-wing aircraft and will require positive control and precision landing capability without using the existing IFR approach path. Furthermore, tilt rotors will not be attractive to passengers if they incur delays and hold times while in flight. We expect that to be commercially attractive, tilt rotors must be able to proceed to their landing areas with the same fluidity as fixed-wing aircraft.

An essential element is therefore an independent landing system that will allow positive precision control of tilt rotors all the way to the ground. The requirements for such a system can best be understood by considering potential routes for tilt rotors when instrument landing systems are required.

Figure 9 shows the ILS approach to runway 22. Assuming instrument landing conditions, all fixed-wing aircraft will enter the ILS approach path within approximately 10–15 n mi of the airport, and reach the outer marker at 5.7 n mi from the runway. This approach path and the runway represent the traffic flow bottlenecks into La Guardia. Prior to entry into the IFR

---

3The FAA Capacity Improvement Program lists LGA as a candidate for a separate short IFR runway using the STOL strip.
Fig. 9—ILS approach to runway 22
system, aircraft will be flying routes that converge near Yoman Int DME (see Fig. 9), 10.7 n mi from the airport at an altitude of 3000 ft. Sequencing for entry into the IFR approach path may occur as far as 50 mi from the airport. Since several routes (between the ILS approach path and the beginning of sequencing) form a single stream in the corridor, these routes may also represent bottlenecks even though separation distances may be well above minimal criteria. For example, if a five-mile separation is the minimum criterion in the ILS, then separations along the four feeder routes must be 20 mi if they are to produce a single stream. Hence sequencing criteria are more stringent than separation criteria.

At distances well beyond the airports, tilt rotors will be flying below the jet routes. They can thus be treated as ordinary fixed-wing traffic and we assume they will not adversely affect capacity. Tilt rotors can continue to be treated as fixed-wing aircraft up to the point of entry into the IFR approach path. This would include the airspace where sequencing occurs, since tilt rotors will not enter the corridor and need only fulfill separation rather than sequencing criteria. However, at a point just before the tilt-rotor and fixed-wing routes converge, the tilt rotor must be treated separately from fixed-wing traffic and brought in on a separate controlled precision approach.

A schematic of this procedure and candidate tilt-rotor routes for a precision approach on runway 22 are shown in Fig. 10. For routes converging from the northwest, the tilt rotor can separate from the converging flow and travel on a route that is roughly parallel to the ILS corridor and separated by at least 2500 ft. For fixed-wing routes converging from the northeast, the tilt rotor will need to maintain a 1000 ft higher altitude over the convergence point until it has crossed to the northwest side of the ILS corridor. The tilt rotor would then have to employ a descent angle of greater than three degrees to arrive at the airport landing area. Use of altitude separation for routes converging from the northwest may also be desirable. A potential altitude profile is also shown in Fig. 10.4

Outgoing tilt-rotor traffic could depart La Guardia in a southwesterly direction and turn eastward to merge with the general traffic flow from runway 13. Such flights would have to be coordinated with incoming fixed-wing flights on runway 22, since the path of the tilt-rotor would move through the airspace used for a missed approach on 22. Coordination with approaches to JFK would also be required.

The situation becomes more complicated when fixed-wing aircraft land on runway 22 and take off on runway 31. In this case, arriving tilt-rotor traffic would have to cross the outgoing paths of fixed-wing traffic taking off on 31. Separations in both altitude and time would have to be coordinated by the controller. Departing tilt rotors would still take off to the southwest, but might then make a northeasterly turn and fly over midtown Manhattan about one mile to the south of outbound fixed-wing traffic.

A less ambitious approach to tilt-rotor operations might involve staying in the ILS approach path until the ceiling has been penetrated. Tilt rotors would then break off from the fixed-wing flow and make a visual approach to the landing area. Although this would not alleviate traffic in the ILS approach path, it would create gaps in the arrival flow on the runway. Since fixed-wing operations on the two runways are coordinated, take-off capacity would be increased on the other runway. Such an approach could be implemented without a new instrumentation system, a distinct advantage. However, it produces only small benefits to the system, and would be unworkable with low ceilings.

---

4The tilt rotor need not use a parallel approach, such as that shown in Fig. 10. It would be possible to define a completely separate approach from the northwest.
Fig. 10—Potential altitude profile
Potential Routes

As shown in Fig. 11, the existing helicopter routes in New York City correspond roughly to the routes described above, suggesting that modification of some helicopter routes may provide the basis for the integration of tilt rotors in the New York system. The Bronx route is roughly parallel to the runway 22 ILS corridor. Given the need to provide angular separation for incoming and outbound tilt-rotor traffic, a direct connection from the Bronx route to La Guardia would be desirable as would a route connecting Throgs to the Marriott route. These proposed routes are shown by dashed lines departing toward the west on the Throgs route. Outbound tilt rotors could exit the city by the Central Park route or by the proposed route to connect the Marriott and Track. It might also be desirable to construct a route directly parallel to runway 22 to obtain maximum angular separation between incoming and outgoing tilt-rotor traffic. Typically, outbound fixed-wing aircraft will not use runway 22 because of noise considerations. However, we expect that the lower frequency of tilt-rotor service and a relatively quick transition to airplane mode should make the tilt rotor relatively quiet when traversing the local community.

The above discussion provides a basis for determining routes for other runway configurations. If, for example, take-off is on runway 4 and landing on runway 13, then tilt rotors would fly the Central Park route for landing. They would need to take-off in a direction roughly parallel to runway 22 and leave the city via the Marriott route.

A potential problem in the approach discussed above may lie in missed approaches on runway 22. The tilt-rotor landing area will be less than 2000 ft from runway 22. In the event of a missed approach on 22, the fixed-wing aircraft will maintain altitude and continue along the direction of the runway. If a tilt rotor is arriving at roughly the same time, there is the potential for wake vortex problems plus a relatively small separation between aircraft. Separation criteria for independent parallel runways in instrument landing conditions are 4300 ft and 2600 ft for a helicopter/fixed-wing combination. Detailed wake vortex measurements will have to be made and relaxed criteria considered if tilt-rotor operations are to be truly independent of the fixed-wing traffic.

Technology and Criteria

Achieving such complex coordination would require modifications and improvements to the existing ATC system. The distance from La Guardia to the crossing point on the East River shown in Fig. 11 is approximately four miles. Assuming that it would be desirable to reverse the flow and use the Central Park route for descent, a six-degree slope would imply an altitude of 2000 ft at the East River. Shallower descents are obviously desirable—perhaps the 1100 ft TCA floor over the East River could be lowered, possibly to the ground. It may be necessary to designate the routes as one-way.

More significant modifications involve implementation of an instrument landing capability that will be able to guide tilt-rotor aircraft into the airport on curved paths and with angles of descent up to six degrees. The Microwave Landing System (MLS), advanced differential Global Positioning System (GPS), precision LORAN, or some other equally advanced navigation and landing system will be required for all-weather operations.6

6A key issue is of course the availability of these technologies at the time the tilt rotor becomes available. MLS could easily be available, given its status in the advanced testing and implementation phase. Other curved approach techniques are being developed independently of the tilt rotor, and might be available in the 1990s, although, as with the tilt rotor, there are remaining financial and technical obstacles.
Under VFR conditions, separation criteria could be waived, and tilt rotors could make a late turn so that they are parallel to runway 11 and the STOL runway. This procedure would allow tilt rotors to maintain the maximum separation from the fixed-wing traffic for the longest possible duration. It would also allow the tilt rotors to use up to 3200 ft for landing, thus effecting significant fuel savings. Tilt rotors could depart along the STOL runway, crossing over either the longer runways or runway 29. This would, of course, depend on the traffic on these runways. An alternative would be to depart directly to the south as shown by the route marked “alternative tilt-rotor take-off” in Fig. 14.

Under conditions warranting the use of an instrument landing system, runway 11 may be closed, and commuter aircraft must line up with the larger aircraft using runways 4 and 22. The east-west runways (11 and 29) do not have ILS. Under this configuration, tilt rotors would have to join the lineup and would contribute to congestion just as do normal fixed-wing vehicles. If traffic at Newark grows, it would be logical to assume that runway 11 will obtain an advanced instrument landing capability, and that the tilt rotor would also need an instrument landing capability. A single MLS capability at the northeast corner of the airport could serve all of these functions.6

Under instrument landing conditions, the assumption that existing separation criteria on parallel runways will be maintained implies that the STOL runway and runway 11 will not be independent, since they are only 700 ft apart. The criterion for independent operation is a 4300 ft separation. At current Newark traffic levels, this lack of independence would not be a problem—tilt-rotor and commuter aircraft could be staggered to provide both lateral and vertical separation. However, if fixed-wing traffic at Newark increases, runway 11 could be at full fixed-wing capacity, thus decreasing the potential for staggering.

We expect, therefore, that under instrument conditions all the way to the ground, the tilt rotor will be forced to land in a vertical mode. As in the case of La Guardia, we do not have criteria for the independent operation of a vertiport near a runway. Detailed wake vortex measurements have not been taken. There are, however, several factors that are likely to enhance the feasibility of independent operations at site 4. Maintaining the offset approach all the way to the landing spot (see Fig. 14) suggests that a significant separation can be maintained for much of the approach. As with La Guardia, the steeper tilt-rotor descent profile will provide altitude separation, thereby reducing requirements for lateral separation. Finally, if runway 11 remains reserved for smaller aircraft, wake vortex problems may not be severe, easing the minimum separation criterion.

Nevertheless, tilt rotors will have to land in proximity (about 700 ft) to fixed-wing aircraft. The above arguments suggest that the requirements for coordinating the arrivals of fixed-wing aircraft and tilt-rotors may not be overly demanding. It is possible that such coordination might be achieved with existing control tower technology.

It should also be emphasized that vertical take-off and landing (VTOL) may not be required if instrument landing conditions are in force. A critical factor is the height of the cloud ceiling. Suppose that fixed-wing aircraft are approaching runway 11 from the west, as shown in Fig. 15. Let us further assume that the tilt-rotor and fixed-wing aircraft are offset by 25 degrees in their approach. The lateral separation between the two approach paths will fall below three miles when the fixed-wing aircraft is 6.43 n mi from the runway and the tilt rotor 7.1 n mi away. However, the fixed-wing aircraft will be in a three-degree approach at 2000 ft altitude. The tilt rotor will be in a six-degree approach at 4400 ft. Under IFR conditions, a

---

6 Simultaneous use of instrument landing on the crossing runways would require an added degree of coordination to allow for the possibility of missed approaches.
1000 ft separation is required, so the planes are not yet in conflict. The aircraft will come within 1000 ft altitude separation only when they are within about 2.75 n mi of touchdown. However, at this point, the fixed-wing aircraft will be at approximately 800 ft altitude, whereas the tilt rotor will be at about 1800 ft. Thus, for ceilings above 2000 ft, VFR conditions might then apply to the landing, and the tilt rotor may be able to use the STOL runway.\(^7\)

Although these calculations provide an optimistic assessment for using site 4 and taking advantage of the STOL runway, actual flight experience will be required to determine whether the above procedures are practical. Without detailed wake vortex measurements, we cannot be certain that the proximity of site 4 to runway 11 will not preclude use of this area for tilt-rotor operations. For this reason, and because of its proximity to the west side of the main terminal structures, site 3 should also be considered as a potential tilt-rotor landing site. An alternative to site 4 will be required for the occasional day when runways 4 and 22 are closed and all large jets operate on runway 11. In addition to the significantly increased wake vortex problem caused by the large jets, aircraft will stage in site 4, blocking the site for tilt-rotor use. In this case, most of the remainder of the airport would be vacant, and the tilt rotor could easily land somewhere on the south side of runway 22. Site 4 or 3 would, of course, provide easier access to the terminals and are preferred.

JOHN F. KENNEDY INTERNATIONAL AIRPORT

Of the three airports under consideration in this study, JFK has the most available space and the greatest degree of flexibility for siting tilt-rotor operations and for conducting those operations with a minimal impact on the airspace. Figure 16 presents a layout of JFK. To provide a sense of scale, runway 13R is over 14,000 ft in length, and the separation between 13R and 13L is almost 7000 ft.

\(^7\)The most recent NASA/FAA study indicated a pilot preference for descents greater than six degrees. Under these conditions, separation altitudes would be even greater than shown in Fig. 15.
Landing and take-off procedures are flexible. Typically, one set of parallel runways is used for take-off and landing, whereas the other parallel set is closed. Under conditions of heavy traffic, 22R might be used for take-off, and 22L and 13R for landing. In this case, the great length of 13R allows incoming aircraft to stop short of 22R, obviating the need to coordinate operations on the crossing runways.

Potential Landing and Take-off Sites

Although there is a great deal of land at JFK, the size of the airport dictates that some tilt-rotor landing spots could be far from the terminals. A major redesign of JFK has been planned that would have linked the separated terminals through a centralized set of passageways, centered on the area 3 in Fig. 17. This project is now on hold. It would have allowed passengers to walk directly between terminals and avoid the bus system that now provides the link for many connecting passengers. We expect that most tilt-rotor passengers at Kennedy will be connectors, and the redesign should significantly improve their ability to connect in a timely manner. Still, the distance across the terminal complex is almost one mile, and if passengers must also endure an extremely long taxiing procedure, the arrangements for connectors could be unacceptable. We therefore assume a high premium for locating tilt-rotor landing sites near the terminal complex.

Figure 17 shows five potential landing areas. Area 1 is at the extreme southeast end of the airport and was once considered for a potential STOL landing and take-off area. It is currently used for cargo operations and is a significant distance from the terminal complex. Area 2 represents the possibility of developing a STOL runway or runways between 22L and 22R and parallel to 13/31. Such STOL runways would be used only when operations at JFK were limited to the 13/31 parallel runways. It would be possible, of course, to coordinate such a STOL runway with operations on 4/22, but such coordination may be inconsistent with our goal of making the tilt rotor independent of fixed-wing operations. In general, tilt-rotor operations conducted from this side of the airport will not be possible with simultaneous operations on 4/22.

An ideal location would be area 3, if the planned centralized walkway system is ever developed. Since the tilt rotor will primarily serve connectors at JFK, this landing area would minimize walking distances for most commuters. However, the structure is not being designed to tolerate tilt-rotor loads. Hence, this option cannot be considered unless the redesign is altered.

For these reasons, if operations are taking place on 4/22, the tilt-rotor landing and take-off site should be located to the northwest of the terminal complex. Tilt rotors can arrive and depart parallel to 13/31, and need not cross existing runways. Area 4 is in a large location where extensive cargo operations take place. Although there may be some available room, careful coordination with cargo activities may be required.

More desirable is area 5, which provides easy access to the terminal structures. However, the status of the area is uncertain. Although the existing taxiway system is likely to be expanded (dashed lines on Fig. 17), there are no fixed plans for use of the space between the terminals and the taxiways. Figure 17 shows one plan for the expansion of the American Airlines terminal. Assuming that the full expansion project takes place, there may be little room for tilt-rotor operations. However, there are many engineering and financial unknowns and the design of the area is in flux, so it can be considered as a potential tilt-rotor site.

---

8There is no specific city ordinance against rooftop landings, but there is a general policy prohibiting the siting of heliports on skyscraper rooftops. Thus, rooftop vertiports might be acceptable at certain Port Authority facilities.
Getting In and Out

The problems in conducting tilt-rotor operations at JFK are similar to those at the other airports, although the size of JFK eases the constraints. When operations are conducted on the 13/31 parallel runways, one will be for landing and the other for take-off. If, for example, 13L is used for fixed-wing landing and 13R for take-off, a strip area near 13L could be used for tilt-rotor take-off. This configuration is illustrated in Fig. 18. Tilt rotors would depart and join the stream of fixed-wing traffic at a point beyond the congested local environment. Arriving tilt rotors would remain in the flow of fixed-wing aircraft as long as they are not a bottleneck (entering the ILS approach path under instrument landing conditions). At that point, they would break away from the fixed-wing flow and form a separate stream as in the situation described for La Guardia. They could land in a vertical mode on the northwest side of the terminal complex. Hence, a flow pattern consistent with the fixed-wing traffic could be established. It may also be possible to bring the tilt rotors into the STOL runway near 13L. Whether this would raise coordination problems with departing fixed-wing aircraft would depend on the traffic and detailed wake vortex measurements. The entire procedure would be reversed when fixed-wing aircraft use runway 31, with the STOL strips being used for landing. If landing is in the VTOL mode on the northwest side of the terminal complex, the distances between the tilt rotors and fixed-wing craft are sufficient to allow independent operations even in instrument landing conditions.

When 22/4 runways are used for fixed-wing operations, use of the STOL strips would be undesirable because of their impact on the fixed-wing traffic. All tilt-rotor operations would then have to be conducted from the vertiport on the northwest side of the terminal buildings. However, the absence of traffic on 13/31 would allow relatively simple procedures for departures and landings of tilt rotors at location 5 on Fig. 17. Weather allowing, tilt rotors could simply use any portion of the 13/31 runway. This situation could also hold when 13R was being used for fixed-wing landings in conjunction with operations on 4/22. Tilt rotors could land on 13R and come to a stop well before interfering with operations on 4/22.

Current practice calls for en route separation of commuters from large jets. This might imply that tilt rotors would be part of the commuter stream using 22/4, while the large jets would utilize 13/31. The same general approach would be applicable. If, for example, large jet takeoff is on 13L and commuter landing is on 22, the tilt rotors could break away from the commuter stream and fly to the west of 13L and approach the VTOL area in this manner (crossing into the VTOL area on the left of 13L as in Fig. 19). A more complicated situation would occur in a scenario in which traffic at JFK increased to the point where all four runways were being tightly coordinated. Tight coordination does not take place under existing traffic loads, but if air traffic continues to increase, it may become a realistic possibility. It is illustrated in Fig. 19. Landing tilt rotors would approach JFK parallel to landing aircraft on 13, approximately one mile displaced from the flow on 13R. They would then make an angular approach to the VTOL landing area. Departing tilt rotors would head almost directly to the northeast crossing runway 13L. They would later turn to merge with the traffic on 4/22 or 13/31 at a point beyond which these streams are congested.

SUMMARY OF THE AIR TRAFFIC CONTROL PROBLEM

The preceding subsections describe basic air traffic control system requirements that would allow tilt rotors to operate at the three New York metropolitan airports. The discussion
Fig. 19—Tilt-rotor operations in a future congested scenario
identifies specific sites and procedures for integrating tilt rotors into the airspace; however, it should be remembered that the vehicle technology could change, airport land use plans may be altered, and certification criteria for the tilt rotor have yet to be determined. Any of these changes could alter the conclusions drawn in the preceding discussions. The key results are the more general conclusions rather than any specific plans. Furthermore, the entire ATC system will evolve as a result of the implementation of the Advanced Automation System (AAS). Data links and precision flexible landing capability will facilitate tilt-rotor operations. Appendix A describes in more detail how AAS would influence tilt-rotor operations.

ATC Requirements and Evolution of the Tilt-rotor Industry

We find from our research that the unique features of tilt rotors offer the possibility of conducting operations at the three airports in a manner that is largely independent of fixed-wing traffic. Additional fixed-wing traffic could be added at Kennedy and Newark and possibly even La Guardia; however, such expansion is ultimately limited by the capacity of the runways and the ILS approach paths. The unique flight profiles of the tilt rotor offer new ways to increase airport capacity, depending on the nature of FAA regulations for tilt-rotor operations.

The need for a new infrastructure, procedures, and technology to achieve such expansion will depend on the levels of tilt-rotor and fixed-wing traffic, and on the visibility conditions at the airports. Assuming visual flight conditions, present fixed-wing traffic levels, and only occasional tilt-rotor operations, few modifications of the existing systems and criteria will be required. These assumptions should be applicable to good weather days in the early stages of a tilt-rotor industry.

However, tilt-rotor operations will require that air traffic controllers accommodate some new operating procedures. Even under optimistic assumptions, tilt-rotor operations will be independent of fixed-wing traffic only with the following procedures:

- Curved path approaches and departures
- Steeper descents (six rather than three degrees) as compared with fixed-wing aircraft

It is also highly desirable to have:

- Multiple locations at an airport for tilt-rotor operations

The latter requirement is important because fixed-wing traffic patterns change with changes in wind conditions. The operations should also be flexible enough to allow incoming tilt rotors to use the runways should excess runway capacity be available during the landing period. Unfortunately, obtaining multiple sites and use of the runways does not seem to be a viable option at La Guardia.

Meeting the above requirements would allow tilt rotors to expand airport capacity under IFR conditions without major expenditures. With low levels of tilt-rotor traffic and IFR conditions, it can be assumed that tilt rotors would enter the ILS approach path and fly under IFR conditions until they broke through the ceiling. They could then fly distinct tilt-rotor routes under VFR conditions to their landing pads. However, the ILS approach path represents a

---

As described in the subsection on La Guardia, this approach might not increase landing capacity but would result in gaps on the runways, thus allowing increased use of a coordinated runway for departures. This procedure requires the assumption that the altitude separation between departing fixed-wing aircraft and steeply descending tilt rotors would be adequate to allow crossings without delays.
bottleneck, and, as tilt-rotor service is expanded, the penalty on the system for entering the ILS approach path will increase. Increasing the level of tilt-rotor service will therefore require:

- An instrument landing capability that can handle curved approaches and steep descents

As the number of fixed-wing and tilt-rotor services increases, there will be a greater need to coordinate arriving tilt-rotor and fixed-wing traffic to ensure that there are no conflicts in airspace. During the initial stages of service, when the number of tilt-rotor flights is low, the extra burden of coordination will probably be handled by the controller in much the same manner conflicts are currently handled. However, the addition of new and distinct tilt-rotor approaches may at some point tax the controller beyond an acceptable level of risk. Conducting tilt-rotor service in a manner that is independent of fixed-wing aircraft will then require:

- An automated data processing system that provides advance notification of a potential conflict and assists the controller in solving the conflict

We cannot now determine when the AAS will be fully implemented. As stated above, tilt-rotor service could be initiated without such aids; operational experience will be needed to determine when they become necessary. The next subsection discusses the advantages of advanced ATC.

ADVANCED AUTOMATION AND A FUTURE TILT-ROTOR SYSTEM\textsuperscript{10}

In this subsection, we illustrate how a future civil tilt-rotor (CTR) system might operate in a far more precisely controlled airspace than now exists. Some of the required technologies are described in App. A. Unfortunately, our crystal ball is too cloudy for us to state when the ATC system will reach the level assumed here. We emphasize that all aircraft, not only CTRs, would benefit from the AAS. Our conceptual CTR is en route from Philadelphia to New York at flight level 90 (9000 ft), traveling at approximately 300 mph, and has been cleared to descend to flight level 40. As the CTR descends, the pilot punches a button on the console keyboard, indicating it is leaving the old altitude for the newly assigned one. Another keyboard entry shifts the frequency from en route to approach control once the assigned altitude of 4000 ft is reached.

All these communications are accomplished in a fraction of the time it takes today because of the ATC's Advanced Automation System. Data link communications between aircraft and ground are key to the automation that will be a vital part of the air traffic management system. Changes in the flight plan or expected weather can be uploaded in seconds from the ATC on the ground to the aircraft. Winds and weather phenomena can be transmitted quickly to the aircraft operating in the system. Beacon codes are used to interrogate the proper aircraft, taking seconds rather than minutes to pass routine information. Advanced surveillance radar coupled with on-board satellite navigation receivers present an accurate four-dimensional position of the cathode ray tube (CRT) to both the air traffic controller and the pilot of the CTR. In addition, all aircraft operating within a specified radius of the CTR are displayed on the cockpit display traffic indicator (CDTI). Surrounding weather can be displayed on the radar scope. When desired, weather data can be uploaded to the aircraft from radar sites covering destination areas.

\textsuperscript{10}This discussion was adapted from inputs provided by System Requirements and Service Associates, a subcontractor to the project.
The CTR's destination is the Manhattan Westside Vertiport. The weather is marginal, with low ceilings and limited forward visibility. Although it is after sunset, the lights of the city are not visible due to cloud cover. An amber light flashes, indicating that the flight plan route has been altered, probably because of a projected conflict in routing. The CTR's progress and routing are constantly monitored by the ATC, anticipating and solving any potential traffic conflict well in advance of its occurrence. At a specified altitude and position, a light flashes on the keyboard indicating clearance approval for an approach into Manhattan. The proper keyboard entry alerts approach control that the pilot has acknowledged the clearance. A cockpit display shows the current route, from the present position to the final approach fix (FAF). This particular approach is a parallel path, adjacent to the ILS approach into Newark. Upon reaching the FAF, the approach curves out over the Hudson River and into the vertiport landing area on the west side of Manhattan.

In the cockpit, the landing area and surroundings appear as a black and white TV image on the radar screen. The river, boats, piers, and buildings in the background are all visible on the radar scope. The CDTI also indicates that an earlier CTR that had been three miles ahead has landed and is taxiing toward the terminal. From the start of his descent, the pilot had monitored the earlier CTR's position, and his displays allowed him to remain exactly three miles in trail as they both approached Manhattan. The radar scope provided a detailed visual presentation of VFR conditions, commonly referred to as "electronic VFR" (EVFR). The EVFR technology would include high-definition radar and forward looking infrared (FLIR) equipment. The pilot has an accurate picture of his surroundings within a distance of 1000 meters (and a 45-degree arc on either side of the nose of the aircraft).

The deceleration from approach to landing speeds is on schedule using the proper deceleration approach techniques (DAT) that have been automatically programmed into the flight director. The CTR arrives over the landing area and enters into an automatic hover. At this point, the pilot assumes full active control and lands the aircraft. Approach control has monitored the entire CTR approach. When the pilot acknowledged that the landing area was in sight, he was turned over to the vertiport tower for landing instructions. This voice report to the tower is the longest voice contact since taxiing out during departure. Yet his progress was monitored constantly, both by ATC and instruments in the cockpit.

The departure of our CTR from the Manhattan vertiport is also routine because of ATC procedures that quickly accept the flight plan and routing. If departing the TCA, the CTR would have received clearance to a departure fix and entered the en route traffic structure along with other aircraft flying in his direction. ATC monitors the CTR's progress, and navigation is precise because of the Microwave Landing System Area Navigation (MLS/RNAV or equivalent) capability. The MLS/RNAV equipment would similarly guide the CTR to JFK, EWA, and LGA landing areas that are distant from fixed-wing approach paths. Using precision navigation to place the CTR on these RNAV routes decreases the controller workload by reducing the need for radar vectoring. Advanced navigational equipment and precision ATC radar will allow this type of operation, with a minimum of control and a high level of monitoring.

If the destination were JFK rather than Manhattan, the CTR would discharge passengers and reload, ready to depart. The next trip will be from JFK to Boston, at flight level 90. The weather, both en route and at Boston, is VFR. Take-off clearance is received and the CTR departs the VTOL area on a departure route that remains clear of all departing fixed-wing aircraft. The CTR is directed toward a departure fix and executes a standard instrument departure (SID), joining the en route traffic flow toward Boston. Transitions through climb and
cruise configurations present no problems for departure control because of speed or climb performance. The CTR is now operating like a typical low-level fixed-wing flight and fits into the en route structure with no difficulty.

The AAS of the future will allow improved ATC management because of precision surveillance equipment coupled with advanced navigation equipment and in-cockpit CDTI monitors that will permit CTRs to operate under IFR conditions with the same precision as under VFR conditions. Surrounding traffic and obstacles will be monitored in the cockpit. The workload of the air traffic controller will not be increased significantly, although the cockpit workload may require two pilots constantly monitoring their progress.

NEEDED MEASUREMENTS

A common problem associated with tilt-rotor operations at the three airports (and probably for airports outside of the New York City area) is the proximity of the tilt-rotor landing area to the existing runways. Borrowing from the analogy of two parallel runways, criteria for instrument landing conditions suggest that operations would be independent only if the landing areas were separated by 4300 ft. Direct application of this criterion would prohibit independent operations at each of the sites identified in the preceding discussion.

Such criteria may not be applicable to the tilt rotor. Tilt rotors have the advantage of approaching the airport at a steeper descent, thereby maintaining an altitude separation from fixed-wing aircraft approaching the runway. Their approach will also be offset from the fixed-wing approach by angles of 25 degrees or more. At this time, we do not know the acceptable combination of altitude and lateral separation for simultaneously approaching tilt rotors and fixed-wing aircraft. Detailed wake vortex measurements and flight testing and experience will be required to establish criteria that allow for both safety and fluid operations.

In addition to the current need for wake vortex measurements, we also require a fuller understanding of the sensitivity of tilt-rotor approaches to wind direction. We have assumed that when landing in a helicopter mode, the tilt rotor will be insensitive to the direction of the wind. Less certain is the validity of this assumption in a VSTOL mode. This assumed insensitivity would give the tilt rotor great versatility, particularly in using areas of the airport shut down because of wind conditions. It would give the tilt rotor a significant advantage over fixed-wing aircraft, but should be verified with careful measurements.
III. AIRPORT TILT-ROTOR CAPACITY AND INFRASTRUCTURE REQUIREMENTS

OPERATIONS AT FREE-STANDING VERTIPORTS

The preceding air traffic control analysis led to identification of sites for tilt-rotor operations at the three major airports. A second set of issues involves the frequency of tilt-rotor operations that can be conducted at these sites and the infrastructure required to meet passenger requirements for convenience and comfort. Although we have outlined a procedure for ensuring that tilt-rotor operations are independent of fixed-wing air traffic, this does not mean that unlimited tilt-rotor operations can be conducted. The number of tilt-rotor verti-pads will determine the frequency of tilt-rotor operations. Although verti-pads require significantly less area than runways, many of the areas we identified in the previous section were small. Necessary terminals and gates will further limit tilt-rotor operations at the airports.

Space requirements for tilt-rotor infrastructure have been studied extensively for free-standing vertiports. Free-standing vertiports might be located at a city center or in a suburb. The FAA has established temporary criteria for tilt-rotor operations at such facilities, and Boeing and NASA have conducted preliminary design studies. To date, there has been little work on establishing similar requirements for operations at airports. In the absence of such design concepts or criteria, tilt-rotor infrastructure concepts for operations at an airport will necessarily be derived from studies of free-standing vertiports.

Such extrapolation is probably not unreasonable, in that city center vertiport concepts have been formulated with the goal of minimizing land use, which is also a necessity at an airport. Figure 20 shows a design of a representative city center vertiport that minimizes land use by raising a three-level structure. Independent auto parking, terminals, and auto rental will not necessarily be required for a vertiport at an airport. The area for the design in Fig. 20 is determined by the land needed for tilt-rotor operations on the third level, not by the associated services on the lower levels.

The tip-to-tip rotor dimension of a 31-passenger tilt rotor is approximately 85 ft. FAA requirements specify a 25-ft separation between vehicles, implying a width requirement of 110 ft per vehicle when parked at a gate. The design shown in Fig. 20 contains five vehicles parked side by side at gates, corresponding to a total of 550 ft. This design cannot accommodate additional tilt-rotor gates.

The two verti-pads represent maximum use of the space. Preliminary FAA criteria do not refer to minimum separation for two side-by-side verti-pads, but do specify a 250 ft square for a single verti-pad. The touchdown/take-off (TD/TO) area is a 100 ft square with a surrounding final approach and take-off area (FATO) of 75 ft width. If we assume that there is no economy in the FATO for side-by-side TD/TO areas, then two verti-pads would require a rectangular 500 ft by 250 ft area. The TD/TOs would be separated by 150 ft. The 500 ft length can therefore accommodate the two verti-pads shown in Fig. 20.

---


3All criteria are tentative at this time. This information was taken from an unpublished FAA draft.
Fig. 20—A representative city center vertiport
The combination of two vertipads and four gates (the fifth parking spot in Fig. 20 is for repair) represents an approximate balance in capacity of the two elements. NASA estimates that each tilt-rotor operation will require six minutes at the pad and 30 minutes at a gate.\textsuperscript{4} Thus four gates can accommodate eight aircraft per hour and two pads allow for 20 operations or 10 aircraft per hour.

**LA GUARDIA**

Of the three airports, La Guardia was most constrained in the choice of tilt-rotor landing spots and in the area available for tilt-rotor infrastructure. The analysis in Sec. II identified several potential landing spots, though each had potential problems. Figure 21 highlights the employee parking area, which was most attractive from the perspective of available area and air traffic control.

The figure shows that the parking area is triangular with sides of 1000 ft, 1000 ft, and 1400 ft. The obvious disadvantage of the parking area is its location on the opposite side of the runway from the main terminal. Figure 21 also shows the road around the airport that would connect this area with the Marine and Main terminal areas.

It would be desirable to have the tilt rotors pull up to the main terminals by crossing the runways. However, this may not be possible. The density of traffic on the runways suggests that tilt rotors may interfere with fixed-wing operations. Because of gate congestion at La Guardia, tilt rotors may not be able to pull up to main terminal gates without interfering with fixed-wing operations. Gate holds are prohibited at La Guardia. The tilt-rotor landing pad could be placed on the terminal side of the runways; however, this site has many problems and the area is small relative to the parking area. As will be demonstrated below, this area is too small to conduct many TDs/TOs, even if the other problems could be overcome.

A basic choice concerning the parking area is whether to build a terminal complex or simply to use landing pads and access services at the Marine or Main terminals. In the latter option, passengers would be transferred via bus or people-mover system. Figure 22 shows that the terminal sized in Fig. 20 can easily fit within the employee parking area. Figure 23 shows that a terminal that is roughly 50 percent larger could also fit into the area if rotated 45 degrees and some additional area is available. Such a terminal would have three landing pads and six or seven gates. NASA estimates the costs of a suburban terminal at $11 million in 1987 dollars.\textsuperscript{5} A suburban terminal does not require the multilevel structure shown in Fig. 20. A better estimate is likely to be the $40 million estimated as the cost for a multilevel terminal with two pads and four gates.\textsuperscript{6}

A major problem with designing a terminal in this area is the level of tilt-rotor traffic. If tilt-rotor traffic (and hence passenger density) is low, there may be inadequate taxi or rental car service in the area, and passengers will be forced to transfer to the Marine terminal. The need for a convenient rental car service was one factor specifically identified in the Albany survey discussed in Sec. V. If traffic is high, automobile access to the area could be a major problem. Because there is little road space the likelihood of congestion is high. A terminal would

\textsuperscript{4}NASA Ames, 1989.


Fig. 21—The employee parking area at La Guardia
also slow down connecting passengers who would obviously prefer a direct link to the other terminals.

It appears to be a more attractive option to move passengers directly from the aircraft to a transportation system that would stop at the Marine and Main terminals. Such a system would bring passengers quickly to auto rental services and connecting flights. For some passengers this would be a disadvantage over a new terminal, in that it might require additional time to reach service areas (such as auto rental if the tilt-rotor terminal traffic justified such an enterprise). However, the entire process might be facilitated by specially designed vehicles that allow arriving commuter passengers direct access to ground transportation. Such a device for large jets is employed at Dulles airport, although it is not uncommon to hear passenger preferences for direct access to the terminal. This approach does address the concern mentioned in the focus groups about avoiding exposure to the elements and seems preferable to the prospect of uncontrolled auto traffic moving from the Marine terminal to the parking area.\textsuperscript{7}

If such an option were pursued, the parking area would consist solely of tilt-rotor vertipads. Gates would not be required. The people-movers would simply pull up to the arriving vehicles and transfer passengers to the main terminals. Figure 24 shows that approximately

\textsuperscript{7}The focus group findings are discussed in Sec. IV.
five 250-ft pads could fit into the area, one of which would be reserved for repairs. Using the NASA assumption of a 42-minute turnaround time, approximately 14 movements per hour could be operated. This is similar to the two-pad, four-gate configuration shown in Fig. 20. It is not as efficient a use of area as the vertiport shown in Figs. 21 and 22. A three-pad, seven-gate vertiport would have a capacity of about 20 movements per hour. This configuration could be duplicated by moving tilt rotors off the vertipads onto a parking area as is done in Fig. 20, although it would not be necessary to actually build gates or the terminal.

We therefore conclude that between 14 and 20 movements per hour could be conducted from the parking lot. As shown in Fig. 1, this may not be adequate to accommodate the approximately 20 commuter operations per hour at La Guardia that would result if tilt rotors capture the entire market, particularly if delays or realistic engineering factors provide constraints not identified here. We should also remember that competition for space at La Guardia is intense, and in all likelihood other users will be anxious to take over the parking area. Should the available area be reduced, further limiting the number of pads, there would be a corresponding reduction in the capacity of the tilt-rotor area. Thus, there may not be sufficient space at La Guardia to accommodate even half of the potential peak commuter demand.

The location of the parking area is another problem. A people-mover system may bring passengers directly to the main terminals, but the transfer time entailed suggests that this
option will not be as convenient as current fixed-wing operations. The analysis in Sec. IX indicates that tilt rotors will have to provide an advantage in convenience and lessening delays to capture a portion of a competitive market, so it seems unlikely that the arrangement described in this section will lead to a viable and enduring tilt-rotor operation. Subsidies or administrative measures would appear to be a prerequisite for sustaining tilt-rotor operations. Indeed, the severely constrained space at La Guardia makes the possibility of a successful and independent tilt-rotor operation highly questionable.

NEWARK AND KENNEDY

As discussed in Sec. II, there are less severe space problems at Newark and Kennedy than at La Guardia. Under visual flight conditions, and even under some instrument conditions, very short take-off and landing (VSTOL) operations should be possible. Additionally, there will be adequate capacity to cope with foreseeable commuter airline loads. Given the number of connectors at the two airports, and the desire for major carriers to be linked closely with the connectors at the gates, it does not seem attractive to construct a special tilt-rotor terminal at
these airports. Use of a special terminal also seems to contradict the stated goal—to conduct tilt-rotor operations at different areas of the airport, depending on fixed-wing traffic patterns. A special terminal would in many cases be far from the tilt-rotor landing area.

Depending on weather conditions and fixed-wing patterns, the analysis in Sec. II showed that it may be necessary for tilt rotors to operate at specified and constrained areas at both airports. These locations were highlighted in Sec. II, and are illustrated again in Figs. 25 and 26.

As can be seen in Fig. 25, the VTOL landing area at Kennedy is approximately 2000 ft by 1000 ft, significantly larger than the area at La Guardia. This obviates the necessity to site gates in this area or leave the tilt rotors on the pads. Instead, the area can simply be used as a landing pad from which the tilt rotors will quickly proceed to their gates. Since the peak load commuter traffic is approximately 20 operations per hour, the NASA assumptions of six minutes per operation, per pad, imply that two pads would be required to accommodate the peak load. Using the assumptions of the preceding subsection, two pads constituting a 500 ft by 250 ft total area would be required. This could easily fit into the area highlighted in Fig. 25. However, it should be remembered that this area is also being contemplated for expansion of the American Airlines terminal. Until such plans are finalized, we cannot be certain that tilt-rotor operations would be feasible.

![Diagram of JFK airport with annotations](image)

**Fig. 25—VTOL tilt-rotor landing area at JFK**

---

8Even Newark has a significant connecting fraction. Our Albany survey indicated that 19 percent of commuter passengers to Newark were connecting, which is consistent with schedule data that reveal a pattern of the bulk of commuter flights arriving approximately one hour before the large jets depart.
The area at Newark is smaller than that at Kennedy, but the 750 ft square area shown in Fig. 26 can accommodate significantly more than the peak load of 20 commuter movements per hour. This conclusion assumes that the tilt rotors can leave the area quickly after landing. During the peak hours at Newark, there may be gate congestion, but unlike the configuration at La Guardia, there is more staging area. Thus, tilt rotors should be able move promptly even if they cannot proceed directly to the gate. If future congestion reaches a point where the tilt rotor must have its own gates, or simply cannot move off the landing pad, then the situation would be much the same as it is at La Guardia. The tilt-rotor landing area could accommodate about six pads, allowing some 24 tilt-rotor operations per hour. However unlike La Guardia, this would occur only when instrument flight conditions dictate use of the VTOL landing area and only during the morning and afternoon surges.
IV. EVALUATION OF TILT-ROTOR FOCUS GROUPS

PURPOSE OF THE FOCUS GROUPS

Although tilt rotors could provide significant advantages to the traveling public, there are uncertainties related to the ultimate size of the tilt-rotor market. The greatest uncertainty arises from the higher tilt-rotor operating costs over conventional turboprop service. Passengers might choose tilt-rotor service only when the perceived convenience and ground travel cost savings were large enough to compensate for the potentially higher fares. A second major uncertainty may lie in public confidence in the tilt rotor. The market has been consistently hesitant about helicopter service, with many travelers voicing concerns about safety and comfort. Few scheduled passenger services survive. It is unclear whether the market will perceive tilt rotors as a helicopter variant, and whether there are steps that operators and developers can take to counter any negative perceptions.

To gain insight into how potential passengers may react, we conducted four passenger focus groups in conjunction with our study for the Port Authority of New York and New Jersey on tilt-rotor use in the New York City area. We hoped the focus groups would help us better understand how the traveling public values point-to-point travel time savings and hence the potential benefits of tilt rotors. Such insights could be helpful in identifying the correct market niche for tilt rotors and in estimating the ultimate market share. We also hoped to introduce the participants to the tilt-rotor concept so that we could monitor initial reactions and identify concerns that might be addressed in the process of planning a tilt-rotor system in the New York City metropolitan area.

STRUCTURE OF THE FOCUS GROUPS

Four focus groups were organized and conducted in May 1989 using a New York City focus group facility. Participants were selected on the basis of their travel patterns, with the primary criterion business travel more than twice monthly for the previous 12 months to destination cities within 500 miles of New York City. Two of the four groups consisted of travelers who typically fly the shuttle service between New York City and Boston or Washington D.C. The other two groups were comprised of travelers who fly commuter aircraft to smaller cities such as Albany, Hartford, Allentown, or any of the other 50 or more cities serviced by commuter aircraft from the three major airports in the New York City region. Although the latter markets are much smaller than the Boston and Washington markets, they are important in terms of the number of aircraft movements and form a significant portion of existing airport capacity.

1Tilt-rotor operating costs may be greater than twice as high as conventional turboprops, although significantly less than helicopters. See FAA/NASA/DoD, Civil Tiltrotor Missions and Applications: A Research Study, NASA CR 177452, July 1987.


3By point-to-point travel time we mean the time required to go from origin to final destination, including ground transit time, time in the air terminal, ATC delays, air travel time, and all travel times required to reach the final destination after landing.

4The focus groups were conducted by Chris Eberhard of Communiquist, a California-based aviation marketing and planning firm. Ms. Eberhard is an aviation marketing consultant with broad experience in eliciting passenger attitudes toward air transportation issues. Screeners were prepared in collaboration with Focus LA, a marketing research firm that specializes in focus group recruiting. Videotapes of the focus group sessions are available from the authors.
A major limitation of the focus groups was our inability to interview travelers residing in other cities who typically fly to New York City for business. All four focus groups were conducted in New York City and all of the participants resided in the New York City area. Passengers flying into New York City from other cities may have different ground travel patterns, may use the New York airports at slightly different times, and may therefore have different perspectives and needs than those initiating travel in the New York City area. The implications of this limitation will be discussed below.

The majority of the participants were middle-level executives or managers employed by large firms or institutions. Each participant was paid $75 for a two-hour session, making it more difficult to attract individuals at very high income levels. Two of the sessions were conducted during the lunch hour and two in evenings after the working day.

REATIONS TO EXISTING TRANSPORTATION SERVICES

A significant portion of the two-hour sessions was spent eliciting participant attitudes toward existing air travel services. Having discussed the existing system, participants were introduced to the tilt-rotor concept through narrative, photographic, and video presentations. The narrative and photos are shown in Figs. 27 and 28.

We will first review participant attitudes toward the existing air transport system, and then summarize participant reactions to the tilt rotor. The final subsection will highlight the potential implications of the focus groups for the development of a tilt-rotor market and for the development of a commercial tilt-rotor vehicle and infrastructure.

Travel Patterns

All of the participants traveled to one of the relevant destinations for business purposes two or more times per month, and have done so for at least one year. Most of the participants used air transportation exclusively for these trips, and the typical business trip was initiated and completed on the same day. Most of the one-day trips originated early in the day from the individual's residence and ended with the return home. Although there were several exceptions to this pattern, most trips did not involve leaving from the office.

Getting to the Airport

Consistent with the basic advantage offered by the tilt rotor, all four groups indicated that the most significant difficulty with the current air transportation system involved getting to the airport. Most felt that the increased ground congestion in the New York City area has made accessing the airport a major problem. As one participant stated,

*New Yorkers consider it a real victory just to get to the airport.*

Another stated,

*It takes a lot more time to get to the airport than the actual flight. . . . That is the stressful part.*

Most participants felt that the problems of ground access were most important in the New York City area. There were few, if any, complaints about ground access at the destination cities, including National Airport in Washington, D.C. and Logan Airport in Boston.

Perhaps even more significant to the participants than the time required to get to the airport was the uncertainty in predicting the travel time to the airport. Many felt that on a
A RAND CORPORATION STUDY ON NEW AIRCRAFT TECHNOLOGY

Modern turboprop aircraft can soon be built in a manner that will allow them to land and take-off vertically, while still offering the speed, comfort, and safety of aircraft that are currently or soon to be in service. The key advance is the ability to rotate the propeller from a vertical to a horizontal position during the flight.

These aircraft have been in experimental operation for many years. The Department of Defense is now flight testing a full sized vehicle and we expect these tilt rotor aircraft to serve destinations within 400 miles of New York City.

This development could offer benefits to air travelers. Since tilt rotors can take off vertically, it may not be necessary to operate these aircraft at existing airports. Mini-airports could be sited at locations far more convenient for most air travelers. This would save travelers ground travel time and help them avoid the congestion and delays associated with utilizing JFK, Newark, or La Guardia airports. New York airport officials and the federal government are also interested in tilt rotors because they could safely expand the capacity of the aviation system, even if they are operated at the three major airports.

Fig. 27—A RAND Corporation study of new aircraft technology

normal day, airport access was not a particular problem, but that unexpected traffic jams forced them to plan long ground transit times. One participant stated,

*I like to leave more than an hour to an hour and a half as you never know about traffic in the morning. One accident on the Long Island Expressway or the Grand Central could throw you off.*

Another stated,

*I am out by 6 a.m. I don’t care how much time I have to spend in the airport ... I don’t want to miss the plane. It’s a terrible feeling to miss an appointment that you have set up.*

Some participants felt the lack of predictability was compounded by unreliable taxi and car services. Because of the lack of a direct rail link to the New York airports and the high parking fees, few were satisfied with their options for getting to the airport.
Fig. 28—Photograph of a tilt rotor
Existing Air Service

In contrast to the problems in getting to the airport, most participants seemed relatively happy with the air portion of their trips. Few, if any, voiced strong concern about delays caused by the air traffic control system, and most felt that the air services were a highly reliable means of transportation.

The focus group respondents using the shuttle service to Boston or Washington, D.C. emphasized the importance and value of flexible ticketing and the frequent service provided by the shuttle. With the large volume of flights and guaranteed seating, many felt that some of the uncertainties associated with ground access were at least partially addressed. Several passengers felt reassured that there would always be another flight in a short time and felt this was a major advantage to air travel to Boston and Washington.

One surprising result emerging from the groups traveling to the smaller cities was the extent to which these individuals enjoyed air travel. They voiced none of the anxieties many passengers feel, particularly in conjunction with the smaller planes they typically fly. Most described the trip as relaxing and expressed a great deal of satisfaction with the air travel portion of their journey.

Travel Costs and Modal Choice

Since tilt-rotor operations would probably cost more than existing fixed-wing service, we wanted to learn more about how fares affect the modal choice travelers make. We asked the participants how their travel patterns might change if air fares rose. Their principal reaction was anger and frustration at the high cost of air travel. They expressed a strong sentiment that the prices were already too high and that any further increases would be intolerable. Although reluctant to name a transportation alternative, some participants said higher air fares would force them to fly less. For example, one passenger stated,

_I would have to reevaluate my business and stop working with these few people in Albany or work some sort of system that they send me what I needed. . . . I would sit down and reevaluate my business._

Another stated,

_If it becomes any more expensive, I am sure that my employer would start questioning it and probably send me by some cheaper means._

Although there was an almost unified angry reaction to the possibility of higher fares, some mitigating factors emerged in the focus groups, potentially implying less sensitivity to fares. The participants may have attempted to guess at hidden agendas for the focus groups, and hence wanted to relay a message about fares, rather than pass along honest reactions. Also, several participants admitted that since their employers paid all travel costs, they personally had little to lose by fare hikes. In the words of one participant,

_I am on an expense account so money is not foremost on my mind all of the time._

Perhaps even more significant was the failure of participants to name an alternative to air travel. Shuttle passengers to Boston and Washington, D.C. felt that the one-day trip could only be made conveniently by air. Most passengers to smaller cities, such as Albany, seemed to have had poor experiences with the rail system, complaining that trains were inconveniently scheduled and often late. Rail was a poor alternative to many since they originated their travel from home, and traveling into Manhattan to access the rail system was perceived as time
consuming and difficult. Some participants had driven to Albany on occasion, many finding the drive long and tiring.

REACTIONS TO THE TILT-ROTOR CONCEPT

After discussing issues related to the existing air transportation system, participants were introduced to the tilt-rotor concept with a film, photograph, and a written summary. The summary and the photograph are shown in Figs. 27 and 28. They were also shown a video of the XV-15 craft landing at the Wall Street heliport after a non-stop flight from Washington, D.C. The four-minute presentation also showed the vehicle making a full transition from a vertical to a horizontal mode.

Reaction to the Overall Concept

All four focus groups understood the potential advantages of the tilt rotor and were enthusiastic about its possibilities. Most of the participants were upset about the difficulties in getting to the three New York airports and could see that the tilt rotor had the potential for alleviating this problem. In the words of one traveler,

*I love the idea of thinking that I could get somewhere from within Manhattan to city to city.
It's terrific that you don't have to commute like we discussed.*

Another stated,

*Boy, if it were on the Westside, near where I live, I'd try it tomorrow.*

Several mentioned the possibility of being able to reduce travel time and increase productivity. For example, one participant stated,

*If it can really cut time, say 50%, corporate accounts would be very interested.*

Some travelers, however, were hesitant about reducing travel times, feeling that a shortened trip might force them to return to the office. As an example, one participant stated,

*I cannot fathom going into the office in the morning when I am leaving. That is ludicrous.
Anybody that does that deserves a medal.*

Several of the participants linked the benefits of the tilt rotor directly to their concerns about difficulty in planning the travel time to the airports. For example, one participant stated that the best thing about the tilt rotor was *predictability in terms of time.* Another stated,

*The last thing you want when you're going to make a presentation is to have to look at your watch every five minutes.* . . .

Based on reactions like these, and the severity of the ground transportation problem facing these air travelers, we conclude that the passengers are receptive to new transportation options, including the tilt rotor. Few, if any, eliminated the tilt rotor as a potential option. However, a variety of concerns and requirements for a tilt-rotor system were expressed, as discussed below.
The Economic Value of Point-to-Point Travel Time Savings

One of the most surprising results of the focus groups was the unwillingness of the participants to pay a significant premium to avoid the problems of accessing the major airports in the New York City area. A majority of the commuters stated they would not pay more than 10 percent above today's air fares for tilt-rotor service, even if the service were conducted at a conveniently located vertiport. A few saw a positive trade-off between time and money and expressed a willingness to pay 15 to 25 percent above normal airfares if significant time could be saved. But a significant number of passengers felt the tilt rotor should not be priced higher than any other air alternative. As one participant stated,

(The) company is already asking to cut down travel . . . So it needs to be in the ballpark, because out of the ballpark, price-wise companies won't go for it.

This group could not understand why travel from different airports (or in this case a vertiport) should involve different fares.

The relatively low acceptable premiums may indicate an unwillingness of many passengers to expend a significant amount of money for the benefits of tilt-rotor service; however, there may be other interpretations. The acceptable premiums were comparable to, or even less than, the taxi or parking fees that most of these passengers now incur in traveling to a major airport. They may not have factored in total point-to-point travel costs, or they may have been reticent about confessing to a willingness to accept fare increases of any kind. In any event, it seems clear that the potential tilt-rotor user must be made more aware of both point-to-point travel times and costs if the tilt rotor is to compete effectively against fixed-wing aircraft at major airports. There may be a tendency for individuals to use air fare and time in the air as the parameters that determine their preferred air option.

Identification with Helicopters

Although the participants were positively impressed with its features, the tilt rotor was perceived in the context of helicopters and most respondents voiced anxiety toward helicopters. As one participant stated,

I love the idea of thinking that I could get somewhere from within Manhattan . . . It's terrific that you don't have to commute like we discussed. I sort of have fear of helicopters that I would have to resolve.

Another stated,

How comfortable is something like that (referring to the tilt rotor)? I have been in a helicopter once and quite frankly I got so shook up. I don't know if I really want to sit in there for an hour and a half.

Typical of other comments was the following,

I don't like that vertical thing . . . it kinda scares me. What if one engine falls off? Sometimes I look at the copters on 64th Street and I'm always afraid that they are going to fall into the river. A big wind will tip them over.

It was also interesting to note that a significant number of the participants had a clear recollection of the helicopter crash at the Pan American building and voiced their apprehension about landing on the top of a building.

Although these perceptions were definite, participants were enthusiastic enough about the tilt-rotor concept to identify factors that would alleviate their anxieties. Perhaps the most
important factor would be a record of successful tilt-rotor commercial operations. As one participant stated,

I wouldn’t buy a new car the first year they make it. I would want to see its performance before
I would do anything, but ultimately, sure.

Another stated,

Even with a government stamp of approval I would still wait and see . . . I just need a track record, no incentive for my body being on the line.

Perhaps the most important reassuring factor to these travelers was the development of a tilt rotor by a recognized manufacturer and operation by a major airline. One participant summarized the feeling of several:

If it’s run by a major outfit and the location is right, I’d take it tomorrow.

Another pointed out that operation within the context of a major airline’s fleet would significantly reduce the unique anxieties associated with the tilt rotor:

If Pan Am started to put this in every other plane, we wouldn’t think twice about it if it became part of their stable of planes.

Another stated,

Major airline—not “tick tock tilt rotor.”

Finally, one participant, noting Boeing’s long track record in commercial aircraft, stated,

I’d make it Boeing-Bell, not Bell-Boeing.

Desired Infrastructure and Vehicle Characteristics

Equally important to these potential users was the precise location of the tilt-rotor service. Operation of tilt rotors at the three existing airports did not seem to be an attractive option for these participants. Most did not feel that their existing service was subject to excessive delays and hence saw no advantage to tilt-rotor operations at existing airports, even if they incurred fewer ATC delays than fixed-wing service or provided easier access through a new terminal arrangement.

Most felt that the tilt-rotor vertiport would have to be fairly close to their residence for them to prefer the service over existing flights. Most agreed that the West side of Manhattan would be an attractive potential site. However, only those living in Manhattan voiced interest in using such a site; the others were interested as a means for drawing off congestion from the major airports. There may have been stronger interest in the Manhattan site if we had interviewed passengers from outlying cities who fly into New York on business. Many of these passengers have to get into Manhattan, whereas the majority of participants in our focus groups were seeking to avoid entering Manhattan. It was also felt that public transportation would have to be integrated into the plans for vertiports to enhance the advantages of point-to-point service.

In terms of vehicle design, the participants voiced concerns about the tilt rotor providing a noisy and rough ride. For example,
Used to commute on a dinky plane—it turns out that the plane can be buffeted around all of a sudden, if you hit a rain storm the plane will drop and bounce all over the place. It (the tilt rotor) looks like it would be like that.

Voicing concerns about the tilt rotor and small planes, another participant stated,

*I think it was six passengers and you felt the vibration, no buffer or insulation in any way... by the time I got off I'd have the shakes all day.*

Several others corroborated this feeling, noting that a noisy flight resulted in a headache and adverse feelings for a period of time far longer than the flight itself.

Many of the participants were obviously drawing a correlation between comfort and vehicle size. Most participants shown film of the XV-15 felt reassured when they were told that the actual vehicle would be larger, closer to the size of their current commuter aircraft. There was, however, a persistent fear that the tilt rotor would have an unacceptable noise level.

In terms of amenities and associated services, the participants in the focus groups seemed willing to settle for relatively austere service on the short flights being contemplated. As one participant stated his needs,

*That it goes up when it is scheduled to go up and comes down when it's scheduled to come down. There are certain amenities that you need. The bathroom. You don't need snacks. You need a decent seat.*

Another stated,

*I don't need the food... it's the anxiety. I care less about the peanuts but the anxiety, especially in bad weather.*

It was also deemed desirable that passengers be sheltered from the elements when entering or departing the aircraft.

**IMPLICATIONS FOR DEVELOPING TILT-ROTOR MARKETS**

**Opportunities and Obstacles**

The four focus groups provided both confirmation of market interest in tilt-rotor services and identification of obstacles that must be overcome before financially viable tilt-rotor services can be established. On the positive side, the participants were nearly unanimous in having experienced the difficulties that the tilt rotor might alleviate. Almost all were receptive to the tilt rotor and seemed willing to consider it as a transportation alternative. Of great concern, however, was the design of the vehicle. The participants stressed the need for demonstrated reliability and the seal of approval from a major airline, manufacturer, and the U.S. government. The participants also expressed interest in witnessing successful tilt-rotor operations for several months.

In addition to expressing concerns about the nature of the vehicle, the discussion indicated that significant market development will be required before tilt-rotor service can capture a substantial percentage of the short-haul traffic out of the New York region. Although Manhattan seems to be the logical location for a first vertiport, the discussions revealed that many travelers leave from their homes, and that getting to one of the three major airports is easier than getting to Manhattan. It is clear that a regional system of vertiports will be required to offer the bulk of the short-haul market significant point-to-point travel time savings. Also disappointing was the relatively low economic value passengers placed on point-to-
point travel time savings, sometimes below the costs incurred in traveling to the major airports. Market awareness can bring home the costs of utilizing a major airport. Finally, the convenience of the frequent service now offered by the Washington and Boston shuttle was to many passengers as important as, or more important than, point-to-point travel time savings. A conveniently located tilt-rotor service may still have trouble competing with the shuttle unless it can offer a comparable schedule. It should also be noted that shuttle operators could compete aggressively against the tilt rotor, perhaps using price or its helicopter-like characteristics to elicit negative attitudes among potential travelers.

**Potential Demonstration Markets**

The above factors point to demonstration markets that might create customer interest in the tilt rotor. One option to consider is service from the commuter cities directly into Manhattan. There are more than 40 flights (in one direction) per day from the New York City airports to Albany, and 36 from Hartford. These are small turboprop aircraft with between 19 and 36 seats. As indicated by our focus groups, passengers accustomed to this type of vehicles seem less prone to anxieties about flying and more apt to consider tilt-rotor service than those accustomed to flying large jets. We recommend study of a market offering direct service from Albany or Hartford to Manhattan. As one step in this process, we recommend surveys to ascertain ultimate passenger destinations and willingness to pay for service from a specific Manhattan site.

The sheer volume of passenger traffic between New York City and Washington and Boston suggests that this market is a candidate for participation in the initial tilt-rotor service. However, it will be difficult to compete with the scheduling flexibility offered by the shuttle. Still, those in a very high income bracket would seem to be an attractive market for a service offering significant point-to-point travel time savings. Such individuals may have a greater sense of the monetary value of their time, and hence would see the advantage of shorter transit times to Washington or Boston in order to allow more time in their Manhattan offices. Demonstration service out of the Wall Street vertiport may be highly desirable for executives in the financial community.

Finally, the focus groups pointed to the need for a thorough and convincing development and demonstration process. The minimization of noise and vibration is likely to be a key element in ultimate market acceptance of the tilt rotor. A lengthy demonstration of the aircraft may be necessary before passengers are willing to consider its use. A subsidy might be structured to test the use of the tilt rotor in noncommercial operations—such as the military, air cargo, or rescue services—before commercial operations become economically attractive.

---

5Based on second quarter 1989 schedules.
V. THE ALBANY PASSENGER AND CORPORATE SURVEYS

RATIONALE FOR THE PASSENGER SURVEY

Issues Addressed

As part of our attempt to characterize potential tilt-rotor markets, we surveyed passengers traveling between the Albany County Airport and the three New York/New Jersey airports. The central objectives of the survey were

- To determine the effects of replacing fixed-wing aircraft with tilt rotors when traveling to the major airports.
- To determine the passenger perceptions of the benefits of landing closer to one's final destination (at a vertiport).

Although operation at city center or regional vertiports is most relevant for the Washington and Boston markets, the analysis in Sec. IX suggests that traffic to Albany is dense enough to capture some city center vertiport operations. Understanding how Albany passengers value travel time savings is also a useful supplement to the focus groups and analytical modeling, where different techniques are employed to gain similar insights.

A copy of the survey is shown in Fig. 29. Respondents were led through a series of questions related to their Albany/New York City trips over the previous 12 months and the trip on which they received the survey. Questions about the trip dealt with final destinations, modes and costs of ground transportation, length of stay, and the costs of the air segment. Question 13 was aimed at determining the price elasticity of demand for air travel. Three distinct survey forms were distributed because of the anticipated tendency to oppose any fare increase. Separate forms with increases of $25, $50, and $100 were circulated with a comparison forming the basis of analysis.

Questions specific to the tilt rotor were presented in questions 14 and 15, with the tilt-rotor concept presented in the paragraph preceding those questions. No attempt was made to describe the tilt rotor in detail. The concept was introduced simply as a vehicle that could bring passengers closer to their final destinations than can conventional aircraft.

Survey Strategy

Our choice of Albany for a single city test survey was driven partially by the importance of Albany as a commuter airline destination. The Albany-New York route is the most heavily trafficked commuter airline route serving New York vertiports. With more than 500,000 passengers per year, route traffic is comparable to popular routes served by commercial jets.\(^1\) A second factor in the selection of Albany was the enthusiasm of the director of the Office of Economic Development at the Albany Country Airport, Mr. Howard Goldstock, who played an essential role in implementation of the survey.

A multi-city survey would have been preferable, but costs dictated a more focused effort. We felt it essential to ensure that the respondents were experienced commuter airline passengers, had recent knowledge of a specific trip, and showed a willingness to accurately

\(^1\)See App. B for comparative data.
ABOUT YOUR TRAVEL

1. In the past 12 months, how many round trips did you make between the New York/New Jersey and Albany airports? Include all flights, whether by air, train, bus, auto, or some other means of transportation. Please count this trip.

TOTAL NUMBER OF ROUND TRIPS: __________

2. How many times did you use each of the following as the main means of transportation for these trips?

AIR _____ AUTO _____ BUS _____ TRAIN _____

3. About what time did this flight leave the Albany County Airport?

Time: ______ AM ______ PM

4. On which day of the week?

[ ] Monday [ ] Tuesday [ ] Wednesday [ ] Thursday [ ] Friday [ ] Saturday [ ] Sunday

5. Which of these is your destination airport for this flight?

[ ] La Guardia (LGA) [ ] Kennedy (JFK) [ ] Newark (EWR)

6. What is your final destination for this flight?

[ ] Lower Manhattan [ ] Midtown Manhattan [ ] Upper Manhattan [ ] Brooklyn or Queens [ ] Long Island [ ] New Haven (CT) [ ] New York/New Jersey destination

7. What ground transportation will you use to reach your final New York/New Jersey area destination? (CHECK ALL THAT APPLY)

[ ] Taxi [ ] Public Transportation [ ] Airport bus/shuttle [ ] Helicopter [ ] Automobile [ ] Other

8. About how many minutes do you think it will take to reach your final New York/New Jersey area destination, from the time you leave the plane to when you expect to arrive?

APPROXIMATE NUMBER OF MINUTES: __________

9. What do you think it will cost for your ground transportation from the New York/New Jersey area airport to your final destination? Include tolls for highways, taxis, car rental, parking, tolls, gas and public transportation.

TOTAL COST: $__________ (IN WHOLE DOLLARS)

10. Is this your outbound or return flight?

[ ] Outbound (1a) How many days will you stay in the New York/New Jersey area?

[ ] I will not stay there [ ] Less than 1 day [ ] 2-5 days [ ] 6-10 days [ ] 11-14 days [ ] 15 or more days

[ ] Return (1b) How many days did you stay in the Albany area?

[ ] Less than 1 day [ ] 2-5 days [ ] 6-10 days [ ] 11-14 days [ ] 15 or more days

11. How much was your airfare for this trip? Was That? ____________ One Way

TOTAL AIRFARE: $__________ Round Trip

(IN WHOLE DOLLARS)

12. Who paid for your airfare?

[ ] Myself [ ] My employer [ ] My family [ ] Someone else

13. If the cost of your round trip ticket had been $50 higher, what means of transportation would you have chosen or would you not have taken the trip?

[ ] Air [ ] Rail [ ] Auto [ ] Bus [ ] Would not have taken trip

14. New developments in technology may, in the future, allow aircraft to be used for private travel and for some other uses. Would you feel comfortable traveling in such an aircraft? If you had been able to take such a trip in the New York/New Jersey area, how likely is it that you would have used it?

[ ] Very likely [ ] Somewhat likely [ ] Somewhat unlikely [ ] Not at all likely

15. If this service were available in the future, what additional service would you not be able to make your ground travel time and avoid landing at a major airport?

ADDITIONAL AIRFARE: $__________ (IN WHOLE DOLLARS)

16. Are there circumstances under which you would not be willing to use this service?

[ ] Yes [ ] What circumstances?

[ ] No

ABOUT YOURSELF

17. What is your occupation?

[ ] Professional/technical [ ] Clerical [ ] Management/administrative [ ] Student [ ] Sales [ ] Other occupation

18. Are you? [ ] Male [ ] Female

19. Are you employed by:

[ ] Government [ ] Private firm [ ] Not employed

20. What is your total household income?

[ ] Under $10,000 [ ] $10,000-29,900 [ ] $30,000-59,999 [ ] $60,000-99,999 [ ] $100,000 or more

If you are interested in learning more about this study or the new technology and would like to participate in a brief telephone interview, please complete this section of the survey. Note: a public interest survey, not a solicitation—you will be asked to purchase anything.

[ ] I AM INTERESTED

Name: ____________________________ Phone: ____________________________

[ ] Business [ ] Home

Best Time to Call: ____________________________

AM [ ] PM

Fig. 29—Survey presented to Albany passengers
complete a lengthy survey form. The survey was conducted in two phases. During the first phase, survey instruments were handed to passengers at the Albany airport as they prepared to board New York City bound flights. The respondents were commuter passengers, had an opportunity to receive an oral explanation of the survey, and could raise questions about the survey’s nature.

The survey implementation required diligence on the part of both survey workers and passengers. Since the Albany/New York City flights range from 19 to 36 seats, many flights had to be targeted. Some 250 forms were distributed during the first phase and the response rate was more than 50 percent, a not surprising result given the time dedicated to each potential respondent. During the second phase, survey forms were enclosed in ticket envelopes by travel agents ticketing Albany to New York flights. As expected, the response rate was far lower. More than 85 percent of the 146 responses were from passengers handed survey forms by Albany airport officials. Although the total number of responses is not large, significant statistical inferences can be made. Undoubtedly, biases still exist in the data base, and the true uncertainties are probably larger than the purely statistical measures presented in the following subsection. However, we judge the data to represent the best attempt to obtain an unbiased sample.

DATA ANALYSIS

Travel Frequency Between Albany and the New York City Area

The first question asked respondents to specify the number of round trips they made between the New York/New Jersey area and Albany during the past 12 months. A histogram of the results is presented in Fig. 30. The average number of trips was 13, the standard deviation of the sample 15.9, and based on 146 data points, the standard deviation of the mean is estimated to be 1.25. With 95 percent confidence, we can state that the mean lies between 10.5

![Histogram showing number of round trips](image)

Fig. 30—Albany/New York round trips during the past 12 months
and 15.6 trips per year. The median was 6, indicating that a small number of passengers do the bulk of the traveling.

Question 1 specifically states that the current trip should be included in the response. Nonetheless, seven respondents indicated that they had not taken any trips. Obviously a misinterpretation has produced a downward bias that is at most one trip if all respondents interpreted the question in this manner.

An average of 13 trips per passenger infers that the sample took almost 2000 Albany/New York City trips during the past 12 months. Figure 31 shows the responses to question 2, which inquired about the mode of transportation for these trips. Air was the primary mode of transportation, with auto or rail as alternatives. Forty-seven percent of the passengers responded that they had taken the auto at least once, with the average (of these 47 percent) being 5.1 ± 1.7 auto trips. Thirty-six percent of the passengers had taken rail at least once, with the average of this set being 8.4 ± 2.7. The average number of air trips was 8.06 ± 2.06. Thus we can be confident that the survey includes an experienced set of Albany to New York City air travelers.

The Current Trip

Question 3 dealt with flight departure time; the results are presented in Fig. 32. The results show that most passengers traveled either at the beginning of the business day or in the afternoon, roughly consistent with the schedule of flights between the two cities. As will be discussed later, most passengers were on one- or two-day trips. Those leaving Albany in the morning were generally Albany area residents planning one or two days of business in New York City. Those departing in the afternoon were generally residents of the New York City area returning, having spent one or two days in Albany.

Question 5 inquired about destination airports. Of the 146 respondents, 141 answered (five didn’t answer) with the following results:

- La Guardia: 82 passengers
- Newark: 43
- Kennedy: 16

![Chart showing modes of transportation](image)

**Fig. 31—Mode of transportation for trips during the previous 12 months**

---

\(^2\)For the remainder of the text, confidence ranges on mean values will be given for the 95 percent level.

\(^3\)Again, all ranges correspond to a 95 percent confidence interval.
These results are a product of our desire to target passengers headed for New York City, rather than a reflection of the distribution of passengers departing for the three airports.4

Final destinations were broken into eight categories in addition to connecting flights from New York City. The data on final destinations are presented in Fig. 33 for the total sample and for those passengers traveling to La Guardia, which currently acts as the “city center” airport.

These results are not inconsistent with the focus groups in that surprisingly few passengers have Manhattan as a final destination. Even for those passengers traveling to La Guardia, only 32 percent ± 4.4 percent intended to go to Manhattan.

It is interesting to note that of the 29 passengers on an outbound trip to La Guardia (originating in the Albany rather than New York City area), 14 (48 percent) had Manhattan as a final destination. Despite this small sample, the result is consistent with the focus groups. Those discussions indicated that passengers originating from New York City tend to return home, rather than to the office, after working in a commuter destination city. A higher percentage of passengers traveling to New York City for business (as opposed to those originating in New York City) intend to travel to Manhattan. The development of a successful Manhattan vertiport may therefore be dependent in part on providing service of such high reliability that passengers returning to New York City can plan to return to the office after conducting out-of-town business.

Although the sample is small, the results are consistent with the hypothesis that most passengers from Albany to JFK are connectors to other flights. Ten of the 15 JFK passengers are connectors. The standard deviation is 12 percent, hence the sample is too small to draw

---

4Using a typical daily schedule for summer 1989 indicates that 14 flights were destined for La Guardia, 20 for Newark, and 10 for JFK.
Fig. 33—Distribution of final destinations
statistical inferences. However, the results do seem to confirm the statements made at the focus groups about the difficulty of using JFK as an airport for short trips.

Ground transportation options were presented in question 7. Figure 34 shows the results of the sample and indicates that the overwhelming fraction of the 114 nonconnectors relied on auto or taxi to reach their final destination. None of the passengers took a helicopter to bring them closer to their final destination. Cost, infrequent service, or anxiety discouraged passengers from using this mode to reduce ground transit time.

Figures 35 and 36 show histograms of the results of questions 8 and 9, which inquired about ground travel times and costs. The average passenger assumed it would require 50 minutes to reach his final destination, with a standard deviation of the mean of approximately 3 minutes. Average travel costs were assumed to be $36, with a standard deviation of $5.
Fourteen passengers estimated no ground travel costs; they may have been picked up at the airport and neglected to recognize the costs of that service.

Questions 10(a) and (b) inquired about the length of stay for the passengers. Most of the passengers stayed only one or two days. These data, and the 77 percent of the passengers that indicated that their tickets were paid for by their employers, suggest that most passengers were on short business trips. This is consistent with our assumptions about passengers most likely to use the tilt rotor.

Reactions to New Service

Questions 13–16 asked for responses to new levels of service, with the latter three questions pertaining particularly to the tilt rotor. Question 13 was intended to help understand the effects of fare increases on modal choice, relevant to the case where tilt-rotor service replaces fixed-wing commuter service, but at a higher price. As stated above, three versions of the survey, with hypothetical $25, $50, and $100 price hikes were distributed. The reactions are compared in Table 1. The values shown are consistent with expectations and are statistically significant. Examining the decision to proceed with the trip or not as a binomial distribution, even with a $100 fare hike, 91 percent of the respondents would still proceed with the trip (the standard deviation is 0.01). Fare hikes of $25, $50, and $100 imply that 24, 35, and 62 percent of the passengers would cancel the air segment of their trip, with standard deviations of 2.8, 3.0, and 3.0 percent.

<table>
<thead>
<tr>
<th>Hypothetical Price Hike</th>
<th>Number of Surveys</th>
<th>Use Air</th>
<th>Use Rail</th>
<th>Use Auto</th>
<th>Cancel Trip</th>
</tr>
</thead>
<tbody>
<tr>
<td>$25</td>
<td>45</td>
<td>34</td>
<td>7</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>$50</td>
<td>49</td>
<td>32</td>
<td>5</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>$100</td>
<td>47</td>
<td>19</td>
<td>9</td>
<td>14</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 1

REACTIONS TO HYPOTHETICAL PRICE HIKES FOR AIR SEGMENT
The results seem to indicate that fare hikes would cause some reduction in the number of passengers carried by aircraft. From Fig. 31, we see that passengers regularly use rail and auto for this trip. Therefore, it seems consistent that these modes would be chosen as alternatives to air travel in response to increased air fare.

Questions 14, 15 and 16 pertained directly to tilt-rotor service at a regional vertiport. Question 14 examines the likelihood of using a new type of vehicle that would bring passengers to the final destination indicated in question 6. The results indicate that 26 percent are either "somewhat unlikely" or "not at all likely" to use the service. Figure 37 shows the results of question 15, which inquired about the willingness to pay for the new service. The figure shows that travelers were willing to pay an average of $47 to land near their final destination. This compares with an average of $36 for ground transportation costs. As average ground transportation times were approximately 50 minutes, this translates into an economic value of only $13 per hour of time saved. This is consistent with the focus group results, although inconsistent with the more empirically based results presented in Sec. VIII.

Questions 17–20 dealt with personal information about the sample. Most of the respondents were employed in the private sector (about 80 percent) and had household incomes of more than $60,000 (about 70 percent).

IMPLICATIONS

Tilt-Rotor Vehicle and Type of Service

The preceding survey elicits both optimism and concern regarding the potential of tilt-rotor service in the New York/New Jersey region. Question 16 addressed the concerns directly by asking passengers about those factors that would prevent them from utilizing the service. Some 60 passengers indicated that there were reasons they wouldn't use such a service. Twenty were concerned about the costs. Although ground travel costs are substantial, there is

Fig. 37—Willingness to pay for vertiport service
a clear focus on the costs of the air segment. This is supported by a low correlation between those with long travel times and the large travel costs. Even when limiting the analysis to passengers taking several round trips between Albany and New York City and to those taking taxis, there was little consensus on the costs per minute of a taxi ride. Clearly people have a much better understanding of the air ticket price than of their ground costs.

The second major concern, mentioned on 14 of the 60 responses, related to the vehicle’s safety or its ability to operate in bad weather. This suggests that substantial time, effort, and marketing may be required before the technology reaches the passenger confidence level enjoyed by current turboprops and jet aircraft.

Finally, 11 survey forms revealed skepticism about convenience, suggesting that the landing location would not be conveniently located or that it would not be well connected to the city’s transportation network. Most often mentioned was the need to have convenient rental car service at the landing location.

Implications for Vertiports

The survey seems to support the notion that the development of a large and busy vertiport could take years to develop. Two survey results support this argument. First is the relatively low value that passengers assign to ground travel time savings. Second, it appears that although Manhattan is the most frequent origin or destination, many travelers start or finish their destinations at home, in the suburbs or other parts of the city. These two factors may be related, in that the capability to depart from and return to the office may enhance the value of time saved and the number of passengers desiring service to and from Manhattan. However, passengers do not yet think in these terms. They seem to require demonstration of a reliable and timely service first.

Implications for Tilt Rotors at Existing Airports

The data do not provide evidence that passengers would be unwilling to board tilt rotors instead of the turboprops they now fly in, but they do suggest that such service to the three existing airports must be implemented with consideration of passenger needs and options. Responses to question 2 clearly indicate that passengers have modal options. Rail service brings passengers directly into Manhattan and is used heavily by a significant minority of the passengers. The automobile is also a viable option for a number of passengers. Combined with the responses to question 13, there is ample evidence that passengers will take other transportation modes if tilt-rotor service results in higher costs to reach existing airports.

This result points to the difficulties in implementing tilt-rotor service at existing airports. If the tilt rotor is competing with fixed-wing turboprops, higher tilt-rotor operating costs could limit its market penetration. It is possible that because of increasing traffic at the airports, commuter travelers may not have an option—the runways will be reserved for larger flights and commuter traffic will be forced onto the tilt rotor. However, the data indicate that without a competing air option, a significant number of commuter passengers would choose rail or auto to reach New York City. Should a “tilt-rotor only” commuter air transportation system maintain the same level of traffic as a fixed-wing system, it would deserve financial credit for its less intensive use of airport resources.


There will of course be ground transportation costs from the vertiport to the final destination. We assume these to be small and for simplicity have not included them in the survey.
THE CORPORATE SURVEY

The focus group and passenger survey analyses revealed that, though concerned with the costs and difficulties of ground travel, passengers were unwilling to pay significant airfare premiums to reduce those costs. Such a result would not be surprising if passengers were answering in terms of their own expenses rather than those of their firms or businesses. Since the business market represents the most likely target for tilt-rotor service, we felt that a more balanced assessment could be gained by asking corporations directly about their travel policies.

To achieve this goal, we sent surveys to 20 travel planners in 20 large Manhattan-based corporations. A copy of the survey and the accompanying cover letter are shown in Figs. 38 and 39. As might be expected, these busy executives were reluctant to take the time to fill out and return such a form. Only two were returned. However, the survey did introduce the corporate travel planners to the tilt-rotor concept, and follow-up telephone interviews were conducted.

Based on these telephone interviews we conclude that:

- Cost is a factor in travel, but not an overriding one.
- There is considerable stress and strain on the traveling executive, and any method of reducing stress and increasing the reliability of air travel is of interest.
- Those willing to estimate the value of greater reliability and reduced stress and strain said that they would be willing to pay 5 to 10 percent more for such a benefit.

The 5 to 10 percent premium was perhaps the firmest conclusion we could draw from the telephone conversations. All five representatives willing to quote a figure mentioned values of less than 10 percent. No representative indicated his firm would be willing to pay more. One representative argued that of the 1000 employees who travel, it would be worthwhile to save time for only 50 of them. He doubted the value of saving time for the remainder. Another mentioned that airfares would have to go up more than 20 percent before his firm would think about reducing air travel.

We found few if any restrictions on executive travel. Despite this freedom, there were few helicopter users. One firm voiced concern about helicopter safety. Another representative mentioned that all employees were required to fly coach unless the trip involved more than a six-hour flight. Even this rule could be tightened when the company was experiencing financial problems. The CEO was the only exception to these restrictions. These results are surprisingly consistent with the focus groups and the Albany survey. Travel planners were concerned about airfares and argued that large price hikes, even with improved service, would not be tolerated.

Formal corporate travel policies may not be explicit enough to make direct inferences about the type of service offered by the tilt rotor. Planners were clearly improvising when they spoke to us. We were unable to transmit anything more than a vague notion of the services a tilt rotor might offer. For these reasons we believe that the focus group format should be used to gain more detailed insights about how corporations might react to tilt-rotor service. Another important point, relevant to our attempts to determine acceptable fare premiums for tilt-rotor service, is the widely recognized disparity between attitudes and actual behavior, in terms of stated willingness to pay vs. actual consumer behavior as measured empirically.
Executive and Middle Management Travel Policies

1. What are the current policies (and/or restrictions) regarding travel for executives?

   a. Are there any ground transportation cost restrictions?
      - bus, taxi, rented car, limo, or helicopter?
      - parking fees or overnight storage?
      - Other?

   b. Air travel restrictions?
      - advanced or discount bookings?
      - first vs business or coach?
      - choice of airline?
      - Other?

2. Are these policies the same for middle management employees when they travel? Yes No. If No, please specify differences in policy.

3. For the commuter traveler (fly out and return in the same day), do you have any additional restrictions relative to:
   
   Yes No
   a. number of trips per month
   b. class of service
   c. ground transportation method
   d. ground transportation costs
   e. Other

   Please explain any YES answer.

Fig. 38—Survey on executive and middle management travel policies
4. Would any of the current commuter travel policies change should air fares rise? Yes __ No __. If Yes, which policies and how?

5. Please try to quantify the degree of fare increase that would trigger such a policy change.

   - __ plus 5%
   - __ plus 10%
   - __ plus 15%
   - __ plus 20%
   - __ plus 25%
   - __ plus 35%
   - __ more than 35%

6. If with the fare increase, new types of aircraft could take passengers directly to and from Manhattan, saving 1/2 hour ground travel time, would that change your answer to question #5? Yes __ No __. Why?

7. If with the fare increase, the ground travel time savings were 3/4 hour, would that change your answer to question #6? Yes __ No __. Why?

8. If with the fare increase, the ground travel time savings were 1 hour, would that change your answer to question #6? Yes __ No __. Why?

9. Do any of your employees currently helicopter services for commuting and/or reaching their take-off point? Yes __ No __. Please explain.

10. Are there any restrictions for this mode of travel for any of your employees? Yes __ No __. Please explain.

Fig. 38—continued
Dear Travel Planner:

The RAND Corporation is conducting a transportation study on behalf of the New Jersey/New York Port Authority. This study evaluates the potential for a new, faster, and more efficient method of air transportation that we believe would better serve Manhattan business executives who frequently travel to Washington, D.C., Boston, Albany, or other cities within 400 miles of New York City.

As part of this study, we are interested in understanding today's corporate travel policies. To this end, we ask that you take just five to ten minutes to complete the enclosed survey. If possible, we would appreciate receiving a copy of your current travel policy for our future reference.

We want to thank you in advance for your time and cooperation. Your responses will greatly assist the Port Authority in planning future air transportation services--services that we hope will better meet the needs of the business traveler.

Should you have any questions concerning the survey, please do not hesitate to contact our marketing consultant, Ms. Christine L. Eberhard, at (213) 546-5713. Because of the timeliness of this survey, we request that you return the survey in the enclosed postage paid envelope no later than August 31, 1989.

Sincerely,

David S. Rubenson
Engineering and Applied Sciences Department

DSR:ee
Enclosure: As noted.

Fig. 39—Survey cover letter
VI. MARKET DEMAND ANALYSIS: APPROACH TO THE ANALYSIS

BACKGROUND

The following sections examine the market potential for tilt-rotor services in more detail, with particular emphases on the opportunities for tilt-rotor service from the three airports in the New York/New Jersey region (La Guardia, Kennedy International, and Newark International), as well as from vertiports at other locations within the region. They use as a point of departure an earlier study for the Port Authority (Hoyle, Tanner and Associates, 1987) that examined the feasibility of a tilt-rotor service network operating at a system of regional vertiports in the New York/New Jersey region.

Our detailed analysis is guided by formal empirically based mathematical models to forecast the growth of markets and the market share that tilt rotors could capture. The models are necessary because the traditional approach for estimating market share is not suitable when radical changes in technology, service, and cost structure are likely. Because the models are explicit and quantitative, they are amenable to sensitivity analysis. In this way a number of significant questions of the “what if?” type are addressed.

Before describing our quantitative methods and findings, it is useful to review the issues and assumptions that shaped our analysis.

ISSUES AND ASSUMPTIONS

The volume of air traffic that might be diverted from existing modes to tilt-rotor aircraft will depend not only on the size of the potential markets that could be served but also on the relative economics of tilt-rotor operations. Since tilt-rotor aircraft are inherently more expensive to operate on a seat-mile basis and have lower cruise speeds than jet equipment, there appear to be three primary situations in which they might have a comparative advantage over existing air service (small market niches might also exist for supplementary service):

- Short- to medium-haul markets\(^1\) now served by commuter carriers using small turbo-prop equipment;
- Intercity markets where the tilt-rotor aircraft can use vertiports in the metropolitan area at one or both ends of the trip; and
- Short- to medium-haul intercity markets now served by jet equipment, if air traffic delays at the New York airports increase to a level where tilt-rotor flight times offer a sufficient advantage to offset the higher operating costs, and if tilt rotors are not subject to similar delays.

The first situation appears to offer significant promise to increase total system capacity, since the existing commuter aircraft take up a significant share of the available runway capacity while handling a relatively small proportion of the total passenger traffic. Thus each

\(^{1}\)Conventional wisdom among commuter operators is that passengers are willing to fly no more than approximately one and one-quarter hours on a turboprop airplane. Thus, the higher cruise speed equipment increases the range of cities commuters can serve to about 300–350 miles from New York City. Small jet aircraft are now being introduced into some short-haul markets.
commuter operation diverted to tilt rotor frees a runway slot that could be used by a larger aircraft carrying many more people. However, the speed differential between a tilt rotor and a small turboprop is small.

For the second and third situation to result in usable markets, the accessibility advantage of the metropolitan vertiports or the saving in flight time would have to be sufficient to offset the higher tilt-rotor operating costs (and presumably higher fares). This assumes that the tilt rotor can use separate approach and departure routes, and can avoid airspace congestion experienced by the fixed-wing traffic. Even if this were to be the case, each tilt-rotor operation will replace only a fraction of a fixed-wing operation, due to the much smaller seating capacity of the tilt-rotor aircraft compared to jet equipment. Significant diversion of fixed-wing jet traffic to tilt-rotor aircraft implies an ability to handle a high volume of tilt-rotor movements.

Since tilt-rotor service is likely to be more expensive than existing air service, it is assumed that tilt-rotor customers will be attracted from those who would otherwise use conventional air service, and not from those using other modes. It is also assumed that no significant change will occur in the level of service of those other modes (such as the introduction of high-speed rail in the Northeast Corridor) that might change current projections of future air traffic during the next 10 or 15 years.

The economic potential for tilt-rotor service in a given market will depend on whether it is the only air service available, whether it is offered in competition with fixed-wing aircraft, or whether it fills a specific market niche as a supplementary service. Since fixed-wing aircraft are likely to have significantly lower operating costs per block hour, and the VTOL advantages of tilt-rotor aircraft may do little to reduce travel times in an airport-to-airport market, it does not appear likely that tilt-rotor aircraft will normally be able to sustain a significant market share in the face of freely competing fixed-wing service between the same points. In the case of service into and out of congested airports, however, certain circumstances may provide tilt-rotor aircraft with a potential advantage. These include:

1. Tilt-rotor service that provides travel time advantages over fixed-wing service, due either to the use of vertiports at the other end of the trip or to air traffic delays that the tilt rotor is able to avoid. Against these advantages must be set possible user aversion to tilt-rotor aircraft (from concerns over safety or comfort) or the relative insensitivity to small differences in time savings for travelers using tilt-rotor commuter service to connect with the banks of jets at Port Authority airports.

2. A need to increase the use of the limited runways by larger aircraft that may lead to time-of-day restrictions, or an outright ban, on aircraft below a certain size. Tilt-rotor aircraft could avoid these restrictions by not using the runway (although they will still need to share the terminal airspace with conventional aircraft). It should be noted that attempts to limit runway use by smaller aircraft are almost certain to be fraught with legal challenge.

3. A change in the current landing fee structure to better reflect the opportunity cost of the use of a runway at peak times. Tilt-rotor aircraft would avoid the significantly higher costs assigned to smaller fixed-wing aircraft using the primary runways. This is a sensitive issue in the light of recent challenges to attempts by the Massachusetts Port Authority to restructure landing fees somewhat along these lines.

4. Airspace and runway congestion that tilt-rotor aircraft can avoid by using other facilities and flight paths, but that significantly increase flight times for fixed-wing aircraft. Sections II and III suggest the possibility that tilt-rotor operations could be virtually independent of fixed-wing arrivals and departures.
5. Direct subsidy of tilt-rotor operations as a more cost-effective way of adding airfield capacity than building new runways or airports. The revenue for subsidizing tilt-rotor operations might come from landing and facility fees paid by larger aircraft that are able to use the slots made available by converting small aircraft traffic to tilt-rotor service. If the opportunity cost of a peak-period landing slot is defined by the delay costs that airlines (and their passengers) are willing to incur to use those slots, these costs could be used to estimate the degree of subsidy that might be possible. The total costs of delay at the three airports in 1985 was estimated at $330 million (FAA, 1987), or about $460 per air carrier operation. Since delay is higher during the peak period, these costs might be as much as $1000 per operation. In 1989, commuter airlines at the NY/NJ airports carried an average of about 14 passengers per operation. If the delay savings from replacing each fixed-wing commuter operation with tilt-rotor service were applied to a subsidy, tilt-rotor operations might be subsidized at $70 per passenger.

Estimates of diversion from fixed-wing to tilt-rotor service at the New York airports should also take account of traffic attracted to tilt-rotor service at vertiports in the New York region. The extent of this traffic will depend on the location of the vertiports and the number of markets served from them.

Given the likely higher total operating costs of tilt-rotor aircraft, fares are likely to be directly competitive with fixed-wing service only if fixed-wing operations have to pay a heavy landing fee penalty. The pricing of tilt-rotor service would depend on a number of factors in addition to the costs of providing the service and the costs of fixed-wing competition. For commuter operators, service and pricing strategies would evolve from their primary goal of enhancing ticket revenues associated with major carrier connecting flights. Travel time advantages for airport-to-airport service are likely to be marginal unless a specially configured ATC system is developed. The potential for service to and from vertiports in other regions depends on the scale of the sub-market between the area served by the vertiport and the New York airports. Such submarkets may exist only in the larger metropolitan areas, such as Boston and Washington. Unfortunately, from the perspective of tilt-rotor market penetration, both those regions have airports fairly close to their central business districts. There may be potential suburban submarkets, such as the Route 128 corridor in Boston or Tysons Corner in Washington.

TILT-ROTOR SERVICE AT REGIONAL VERTIPORTS

Tilt-rotor service at urban vertiports will offer access time and ground travel cost advantages to travelers whose trips begin and end closer to the vertiport than the airport. Against this must be set any frequency and fare disadvantage of the tilt-rotor service compared with the conventional air service. Because of the smaller market served by each vertiport, it is likely that tilt-rotor service frequencies at regional vertiports will be lower than for competing services at the existing airports, except perhaps for the very largest markets. It is also likely that tilt-rotor costs (and hence fares) will be higher. If air traffic delays at the existing airports increase significantly, there may also be some air travel time advantage for tilt-rotor services at the regional vertiports, provided the tilt-rotor aircraft can avoid the congestion themselves.

Therefore, the central question of the viability of such services becomes whether the access advantages are enough to offset these other factors. Since the frequency disadvantage can always be reduced by operating more flights at a lower load factor, at the price of increased
fares, the answer to this question will be highly dependent on how the travelers value time savings. There may not be a single answer to the size of the potential market. Tilt-rotor service could offer high frequency at a very high fare, with low seating density and high levels of inflight amenities, targeted at a relatively small number of travelers with a high value of time, or it could target a larger, more cost-sensitive market, in which travelers are willing to tolerate less frequent service in exchange for a smaller fare differential with conventional service. Another important issue is that the most promising destinations for tilt-rotor operations are Boston and Washington, which are already served by jet shuttles. A single jet has the passenger capacity of three to five tilt rotors of the size we believe most feasible in the next 10 years. This implies more aircraft rather than less, a possible disadvantage, depending on where the additional aircraft must operate in the National Airspace System.

SLOT ASSIGNMENT

Slot assignment could be a mechanism for promoting tilt-rotor operations at congested airports. La Guardia and Kennedy are slot-restricted airports. They are currently designated as high-density airports by the FAA and specific numbers of allocated IFR operations (slots) are reserved for three classes of users: air carriers, commuters, and other. Commuter slots may not be used for carrier operations, but carrier slots can be used for commuters.

The current regulatory capacity limit for commuter designation is 75 passengers, a number that might increase over time. An increase in the limit would permit greater enplanements without increasing aircraft movements. Slots may be bought and sold; the current price of a commuter slot is $100,000–200,000 (depending on the airport and time of day), compared to about $1 million for a carrier slot. Looking at JFK, for example, we find that commuter slot restrictions are imposed for five hours, starting at 3:00 p.m., and average about 12 operations per hour, compared to an average of 72 per hour for air carriers and two for other operations.

With the emergence of regional airlines owned and operated by major airlines or that codeshare with them, it seems clear that a balance is required between commuter and carrier slots to properly feed the larger equipment. Although we have not studied commuter operations in depth, preliminary evidence suggests that the primary objective is to provide additional fare revenues for the associated major carrier by connecting with jet service at hub cities.

Should the FAA permit commuter slots to be used for carriers, then the price of the slot would be set by the value of the alternative service. Both airlines and airport operators might wish to see the substitution of larger equipment that could also serve longer-haul jet markets.

The relatively low market price of a commuter slot suggests that either gate or ramp space is a limiting factor, or that commuter operators are not keenly interested in expanding prime-time operations.

ANALYSIS APPROACH

The assessment of the potential market demand for tilt-rotor service in the NY/NJ region was based on the following steps:

1. Identify all air service markets within tilt-rotor range of the New York airports, and determine existing local traffic volumes.
2. Project traffic volumes to 1995 (assumed date for established tilt-rotor service), 2000, and 2005 on the basis of FAA terminal area forecasts.
3. Review data on intercity travel volumes by surface modes and estimate the share of the markets within tilt-rotor range now using air travel, and hence find the likely size of the total intercity market.

4. Define a mode choice model to predict the proportion of travelers using alternative modes in each market (including tilt rotor) as a function of fare and travel time (flight time and ground access).

5. Develop scenarios covering relative tilt-rotor and fixed-wing fares, average air traffic delays for fixed-wing operations, and traveler value of time.

6. Explore potential systems of regional vertiports in the NY/NJ, Boston, and Washington regions and estimate the share of the market accessible to each, on the basis of air passenger ground origins from recent passenger survey data.

7. For each scenario, use the mode choice model to guide estimates of tilt-rotor market share and traffic in each air service market, and hence to project the total tilt-rotor market.

This analysis approach assumes that tilt-rotor traffic is attracted from other modes and that there is no increase in total intercity travel as a result of the introduction of tilt-rotor service. However, tilt-rotor service will attract those who find the cost acceptable and the convenience worthwhile. Basic concepts of travel demand state that any reduction in travel disutility should result in an increase in total travel. So there may be a modest increase in passengers who are not deterred by the higher fare. Any attempts to estimate demand elasticity effects would be highly conjectural. Furthermore, the costs of tilt-rotor service are likely to reduce its attractiveness to travelers who would otherwise use auto, rail, or bus. In some instances where adequate rail service exists between central business districts, travelers would use air transport modes primarily to connect with jets operating at the Port Authority airports.

It is recognized that 1995 is too early for significant tilt-rotor service. The most recent NASA-FAA schedule (February 1991) suggests 1999 as the delivery date for an aircraft of the type envisioned by our study. Thus, our projections should be interpreted in the following way: if tilt-rotor service were fully established and air traffic was at its predicted 1995 levels, what would be the extent of tilt-rotor market penetration under a variety of system configuration scenarios?

POTENTIAL FOR TRAVEL TIME REDUCTION

To supplement the foregoing analysis, we examined the point-to-point travel time advantages that an extended tilt-rotor system might provide air travelers in the NY/NJ region. This examination could then support a more detailed assessment of the potential for tilt-rotor service at vertiports located close to centers of demand in the metropolitan regions. The analysis was based on zone-to-zone travel times and travel demand matrices for the NY/NJ area and the two major destination cities, Washington, D.C., and Boston.

The demand analysis was incremental. In the baseline case, a downtown vertiport competes with airport fixed-wing service to major destinations, primarily Boston and Washington, but a number of other cities as well. From Port Authority data, we note that 25 percent of air passengers could be served by a downtown vertiport, far more than might be served by any other vertiport location. An average saving of 45 minutes was used to represent the difference in ground access time between the downtown vertiport and airports.
For the baseline case, we forecast both market share and configuration for a tilt-rotor system operating from a Manhattan vertiport. We also examined ground access times for a number of locations in the New York/New Jersey area, hoping in this way to identify promising sites for a fully dispersed vertiport system. Since the downtown site serves the greatest number of potential passengers, only if the downtown site forecasts appeared sufficiently promising did we intend to proceed with a detailed analysis of a regional vertiport system.
VII. MARKET DEMAND ANALYSIS: POTENTIAL MARKETS

The potential diversion of intercity traffic from existing modes to tilt-rotor aircraft will obviously depend on both the economics of tilt-rotor operation compared with those modes and the size of the potential markets that could be served by tilt-rotor aircraft. To estimate the potential size of tilt-rotor markets, future air traffic volumes between the New York/New Jersey airports and communities within 500 miles of the region were estimated for three forecast years: 1995, 2000, and 2005.1 Although tilt-rotor service from regional vertiports might also attract some traffic from surface modes, our judgment is that any such diversion would be negligible compared to the diversion from fixed-wing traffic.

Another issue is that airline decisions about hubs, service, and entry into or departure from a specific market will influence growth patterns for future markets and the division between air carrier and commuter traffic in ways that are largely unforeseeable. This suggests that a simplified aggregate forecast methodology (like that described in Sec. VIII) is suitable for estimating the total number of passengers who might be served by a tilt-rotor system.

Our sense of the current state of civil tilt-rotor technology and development is that a civil variant derived from the V-22 is the most probable aircraft type to be offered for commercial service during the next decade or so. Such an aircraft is likely to have an economical one-way range of 350 n mi, as well as the ability to carry at least 31 passengers. Although smaller tilt-rotor aircraft may be developed, our judgment is that an aircraft of at least a 31-passenger size is required for the New York market to match the economies of scale associated with the probable increase in capacity of turboprop commuter airplanes now being ordered. We have also assumed that vibration, noise, cabin pressurization, ride quality, and amenities would be comparable to those of a contemporary commuter aircraft. A small variant might be useful as a demonstration and public relations vehicle, but a serious tilt-rotor system providing tangible benefits to the Port Authority requires at least a 31-passenger vehicle. A larger tilt rotor carrying as many as 75 passengers would be desirable for some markets, but would not efficiently serve smaller submarkets using dispersed vertiports (both in the Port Authority region and elsewhere). Furthermore, the technology required for a 75-passenger aircraft is not likely to be available soon without a dramatic commercial development effort.

Table 2 presents forecasts for all carrier and commuter markets within 500 miles of New York City. We project a total of 28 million origin-destination (O-D) passengers annually in 1995, growing to 34 million by the year 2000 and 39 million by 2005. Using 350 n mi as an upper one-way distance cutoff, we forecast 22 million passengers in 1995, 26 million in 2000, and 30.2 million in 2005. Thus, the 350 n mi cutoff reduces the potential market size by about one-fifth.

Table 3 lists cities outside the 350 n mi limit that are promising in terms of passenger volume.

---

1Existing (1987) origin-destination traffic was obtained for certificated carriers, commuters, and the Canadian market. FAA terminal area forecasts for 1995, 2000, and 2005 were used to predict enplaned passengers by airport, and the Canadian Airspace System Plan was used to forecast Canadian growth rates. It was also assumed that PANYNJ airports maintain a constant share of all trips beginning or ending in any other market. In this way, 1987 data were used to project future origin-destination traffic in each market.
Table 2
FORECASTS OF AGGREGATE TO AND FROM NEW YORK PASSENGER TRAFFIC
(1000s/year)
(a) Cities <500 n mi from New York

<table>
<thead>
<tr>
<th>Location</th>
<th>1987</th>
<th>1995</th>
<th>2000</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Washington/Boston</td>
<td>7,029</td>
<td>9,305</td>
<td>10,640</td>
<td>11,924</td>
</tr>
<tr>
<td>Other U.S.</td>
<td>10,313</td>
<td>17,033</td>
<td>20,916</td>
<td>24,850</td>
</tr>
<tr>
<td>Total</td>
<td>17,342</td>
<td>26,338</td>
<td>31,556</td>
<td>36,774</td>
</tr>
<tr>
<td>Canada</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cities</td>
<td>1,381</td>
<td>1,847</td>
<td>2,173</td>
<td>2,556</td>
</tr>
<tr>
<td>Total</td>
<td>18,723</td>
<td>28,185</td>
<td>33,729</td>
<td>39,330</td>
</tr>
<tr>
<td>All cities (U.S. and Canada)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–350 n mi</td>
<td>15,524</td>
<td>22,027</td>
<td>26,064</td>
<td>30,238</td>
</tr>
<tr>
<td>351–500 n mi</td>
<td>3,199</td>
<td>6,158</td>
<td>7,845</td>
<td>9,092</td>
</tr>
<tr>
<td>Total</td>
<td>18,723</td>
<td>28,185</td>
<td>33,729</td>
<td>39,330</td>
</tr>
</tbody>
</table>

(b) Markets with >100,000 passengers, 1995, <350 n mi from New York

<table>
<thead>
<tr>
<th>Location</th>
<th>1987</th>
<th>1995</th>
<th>2000</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canada</td>
<td>13,479</td>
<td>19,237</td>
<td>22,193</td>
<td>26,410</td>
</tr>
<tr>
<td>Total</td>
<td>14,775</td>
<td>20,970</td>
<td>24,262</td>
<td>28,808</td>
</tr>
<tr>
<td>Percent passengers &lt;350 n mi</td>
<td>95</td>
<td>95</td>
<td>95</td>
<td>95</td>
</tr>
</tbody>
</table>

Table 3
CITIES 350 TO 500 N MI FROM NEW YORK WITH PASSENGER VOLUME > 100,000 IN 1995
(1000s passengers/year)

<table>
<thead>
<tr>
<th>City</th>
<th>1987</th>
<th>1995</th>
<th>2000</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleveland</td>
<td>708</td>
<td>921</td>
<td>1,069</td>
<td>1,198</td>
</tr>
<tr>
<td>Columbus</td>
<td>433</td>
<td>1,250</td>
<td>1,761</td>
<td>2,272</td>
</tr>
<tr>
<td>Detroit</td>
<td>1,095</td>
<td>1,606</td>
<td>1,912</td>
<td>2,219</td>
</tr>
<tr>
<td>Greensboro</td>
<td>372</td>
<td>513</td>
<td>626</td>
<td>739</td>
</tr>
<tr>
<td>Raleigh-Durham</td>
<td>498</td>
<td>1,743</td>
<td>2,141</td>
<td>2,496</td>
</tr>
<tr>
<td>Total</td>
<td>3,106</td>
<td>6,033</td>
<td>7,499</td>
<td>8,924</td>
</tr>
</tbody>
</table>
Table 4 lists candidate cities and their projected traffic during the 1987–2005 time frame. We assume that a 1995 forecast of a minimum of 100,000 annual O-D passengers established the minimum market size that could support tilt-rotor service. We later modified this in favor of a cutoff based on a minimum of two round-trips daily. The 100,000 passenger screen eliminates about five percent of potential passengers. In addition, we show the 1987 fraction of each city's New York passenger volume that was served by commuter airlines. We recognize, as noted above, that the division between commuter and carrier operations varies as a result of market decisions by individual carriers that are difficult to predict over the long run. For analysis, we assumed that commuter shares do not change markedly over the period of the forecast. We expect, but cannot prove rigorously, that our aggregate forecasts would not be overly sensitive to the precise split for each city.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Boston</td>
<td>3,899</td>
<td>4,888</td>
<td>5,712</td>
<td>6,535</td>
<td>3</td>
<td>67</td>
</tr>
<tr>
<td>Washington, D.C.</td>
<td>3,130</td>
<td>4,417</td>
<td>4,928</td>
<td>5,389</td>
<td>6</td>
<td>38</td>
</tr>
<tr>
<td>Pittsburgh</td>
<td>935</td>
<td>1,589</td>
<td>1,887</td>
<td>2,193</td>
<td>0</td>
<td>38</td>
</tr>
<tr>
<td>Buffalo</td>
<td>950</td>
<td>1,279</td>
<td>1,541</td>
<td>1,804</td>
<td>0</td>
<td>34</td>
</tr>
<tr>
<td>Norfolk</td>
<td>595</td>
<td>816</td>
<td>992</td>
<td>1,169</td>
<td>0</td>
<td>56</td>
</tr>
<tr>
<td>Syracuse</td>
<td>516</td>
<td>701</td>
<td>855</td>
<td>1,009</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Baltimore</td>
<td>411</td>
<td>661</td>
<td>846</td>
<td>1,036</td>
<td>39</td>
<td>21</td>
</tr>
<tr>
<td>Providence</td>
<td>372</td>
<td>578</td>
<td>621</td>
<td>664</td>
<td>74</td>
<td>14</td>
</tr>
<tr>
<td>Philadelphia</td>
<td>369</td>
<td>565</td>
<td>676</td>
<td>793</td>
<td>70</td>
<td>15</td>
</tr>
<tr>
<td>Albany</td>
<td>352</td>
<td>541</td>
<td>640</td>
<td>739</td>
<td>74</td>
<td>14</td>
</tr>
<tr>
<td>Portland</td>
<td>265</td>
<td>486</td>
<td>693</td>
<td>968</td>
<td>7</td>
<td>34</td>
</tr>
<tr>
<td>Hartford</td>
<td>292</td>
<td>417</td>
<td>509</td>
<td>601</td>
<td>51</td>
<td>13</td>
</tr>
<tr>
<td>Richmond</td>
<td>224</td>
<td>311</td>
<td>382</td>
<td>453</td>
<td>2</td>
<td>32</td>
</tr>
<tr>
<td>Burlington</td>
<td>196</td>
<td>306</td>
<td>381</td>
<td>455</td>
<td>2</td>
<td>21</td>
</tr>
<tr>
<td>Worcester</td>
<td>109</td>
<td>264</td>
<td>323</td>
<td>382</td>
<td>32</td>
<td>16</td>
</tr>
<tr>
<td>Manchester</td>
<td>100</td>
<td>256</td>
<td>394</td>
<td>533</td>
<td>32</td>
<td>9</td>
</tr>
<tr>
<td>Harrisburg</td>
<td>83</td>
<td>149</td>
<td>182</td>
<td>219</td>
<td>96</td>
<td>14</td>
</tr>
<tr>
<td>Atlantic City</td>
<td>38</td>
<td>104</td>
<td>158</td>
<td>205</td>
<td>100</td>
<td>—</td>
</tr>
<tr>
<td>Total</td>
<td>12,836</td>
<td>18,328</td>
<td>21,717</td>
<td>25,147</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percent increase over 1987</td>
<td>43</td>
<td>69</td>
<td>96</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Montreal</td>
<td>512</td>
<td>684</td>
<td>805</td>
<td>947</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toronto</td>
<td>784</td>
<td>1,049</td>
<td>1,234</td>
<td>1,451</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1,296</td>
<td>1,733</td>
<td>2,039</td>
<td>2,398</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
VIII. MARKET DEMAND ANALYSIS: MODELS, PARAMETERS, AND INTERPRETATION

MODELS

Mode Choice

Since we have no current operational experience with tilt-rotor aircraft, any attempt to model the choice between tilt-rotor and fixed-wing service must be based on models of analogous situations. The logit model has been widely used for both mode choice and airline route choice applications, and appears to be applicable to modeling the choice between tilt-rotor and fixed-wing service in a given market. The formulation for the utility functions is:

\[ U(i) = a_0 + a_1 \text{FARE}_i + a_2 \text{SCHD}_i + a_3 \text{FLT}_i + a_4 \text{ACT}_i \]

where

- FARE = airfare
- SCHD = schedule delay
- FLT = flight time, including air traffic delays
- ACT = access time to terminal
- \( a_0, a_1, a_2, a_3, a_4 \) = calibration parameters

If there are \( k \) different modes, the share for the \( i^{th} \) mode is

\[ \frac{\exp(U(i))}{\sum_{j=1}^{k} \exp(U(j))} \]

The mode-specific constant \( a_0 \) captures effects that influence choice other than the variables explicitly included in the model, such as cabin comfort, ride-quality, safety perceptions, and so forth. In a two-mode application like the present one, the constant will appear only in the utility function for one mode (taken as the tilt rotor in this analysis), and measures the difference between the two modes. The schedule delay term measures the effect of frequency on the attractiveness of alternative services. It is traditionally measured as half the headway, under the assumption that travelers' desired departure times are uniformly distributed between actual departure times. Some authors have suggested that a lower value may be more appropriate, particularly when using an average headway over the day, since flights tend to be scheduled to match departure peaks. However, this would simply change the value of the parameter \( a_2 \). The access time variable includes other access-related factors, such as taxi fare or automobile operating cost, where these vary with the distance to the terminal. Thus, it can be expected to have a different parameter value from the flight time parameter. Access differences between the two services that do not vary with distance, such as time spent in the terminal or parking charges, will influence the value of the mode-specific constant. We refer to App. B for details regarding the choice of parameter values \( a_0, a_1, a_2, a_3, \) and \( a_4 \). On the basis of the approach described in App. B, the following parameter values were selected, depending on the implied value of time: if travel time is valued at $25 per hour, then \( a_0 = -1.5 \),

---

\[ a_1 = -0.04, \quad a_2 = -1.2, \quad a_3 = -1.0, \quad \text{and} \quad a_4 = -1.17. \]  
If travel time is valued at $50 per hour, then \[ a_0 = -1.5, \quad a_1 = -0.02, \quad a_2 = -1.2, \quad a_3 = -1.0, \quad \text{and} \quad a_4 = -1.17. \]

The tilt-rotor mode-specific parameter value was based on the dummy variable parameter value for aircraft with less than 30 seats in the Kanafani and Ghobrial model (1985). As noted in App. B, it is consistent with results derived by other approaches. The parameter value thus does not account for any additional perceived disutility due to the tilt-rotor technology itself. Sensitivity analyses were performed using different values of \( a_0 \). In general, our baseline forecasts are based on values of \( a_0 = -1.5 \) for both turboprop and tilt-rotor aircraft, and \( a_0 = 0 \) for larger jet equipment. Because our analysis compares only two competing modes for any given market, only the difference in \( a_0 \) values appears in the relationship for market share. As noted in App. B, our choice of values for the small plane penalty is consistent with other data. The access time parameter includes an allowance for access costs of $0.07 per minute, based on the implied automobile operating cost from the model calibration by Gosling (1984a), adjusted to 1987 dollars.

**Logit**

The use of a logit choice model can produce what may appear to be counterintuitive results, in which even a service that has longer travel times and higher fares than its competition may be predicted to attract a small but significant market share. Yet at first sight, it would appear that no traveler would choose it, when a faster, cheaper service is available.

However, it should be remembered that the model is intended to represent the choice of an average traveler facing average fares. In practice, fares may vary widely due to discounts and restrictions, and travelers will have significant variation in income and hence value of time. Other factors not included in the model, such as time-of-day effects and trip purpose, will influence the traveler's choice of service, leading to some use of tilt rotor, even when it is an inferior mode. A less aggregated approach would account for differences between business travelers and others, but the parameters for such a more refined model are not available.

**Other Analysis Approaches**

Although the multinomial logit choice model has been widely used in travel demand studies of the type required by the present study, other analytical approaches are possible.

One widely used approach for assessing the effect of service changes is elasticity analysis. This approach attempts to express the percentage change in traffic using a particular service as a ratio of the percentage change in some causal factor, such as fare or travel time, either for the service in question or for some competing service (in which case it is termed a cross-elasticity). Elasticity values can be obtained by direct observation of the results of implementing some change in the system, after correcting for any changes in other factors that may have affected the outcome, or by derivation from the parameters of a demand model that have been estimated by econometric techniques. There are two obvious difficulties with trying to use such an approach to estimate tilt-rotor demand. The first is that there is no empirical experience from which to either observe changes or estimate models. The other is that the introduction of an entirely new mode represents an infinite change of service on that mode. Therefore, this approach was not considered appropriate for the current study.

The logit model is known to have a number of characteristics that are intrinsic to its mathematical structure and that may be undesirable in some circumstances. For example, the introduction of a new alternative draws traffic from all the other alternatives in proportion to their shares in the absence of the new alternative, including a new alternative that is identical to an
existing alternative (the so-called independence from irrelevant alternatives issue). Some travel demand researchers have therefore tended to favor an alternative formulation, termed the probit model. Unfortunately, experience with this model is more limited, and no examples of calibrations of appropriate probit models for intercity mode choice could be located in the literature.

Other approaches include the direct estimation of aggregate travel demand models, as discussed at length by Kanafani in his book. However, this approach cannot be applied in the absence of empirical data. Therefore, it was concluded that the multinomial logit choice model was the only practical analysis approach.

PARAMETERS

Market Service

Demand for tilt-rotor service in specific markets will depend on the comparative costs and travel times offered by competing modes. For markets within the tilt-rotor range, competing modes will be fixed-wing air service, highway (automobile and intercity coach), and (in appropriate markets) rail. As discussed earlier, tilt-rotor market share is not likely to be gained from surface transportation modes.

Tilt Rotor

Information on likely future tilt-rotor operating economics is still conjectural and limited. The most comprehensive data currently available are contained in the 1987 FAA/NASA/DoD study and the 1989 NASA Ames draft. Fragmentary information can also be obtained from technical press articles on the V-22 and EuroFAR programs. More recent results, dated February 1991, were received too late to be included in our analysis.2

The data suggest a cruise speed of up to 300 kt, with block times over a 200 n mi stage length of 220 kt. The V-22 is expected to have a top cruise speed of about 300 kt. These data suggest a block time relationship given by: BH = 0.25 + SL/300 where BH is the block time in hours and SL is the stage length in nautical miles. Fifteen minutes may be an optimistic estimate for the terminal component of the block time, particularly if rolling rather than vertical take-offs and landings are used, and if the aircraft must taxi some distance to the runway or encounters any taxi delay. The times shown in text table (a) might result from a typical flight using short runways at existing airports.

Table (a)

<table>
<thead>
<tr>
<th></th>
<th>minutes</th>
<th>n mi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxi to runway (1000 ft)</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Take-off and climb to 1500 ft</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Cruise climb to 16,000 ft at 200 kt</td>
<td>14.5</td>
<td>48</td>
</tr>
<tr>
<td>Descend from 10,000 ft at 250 kt</td>
<td>5.0</td>
<td>21</td>
</tr>
<tr>
<td>Approach from 5000 ft at 100 kt</td>
<td>3.5</td>
<td>6</td>
</tr>
<tr>
<td>Final approach from 1500 ft</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Land and taxi to terminal (1000 ft)</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>28.0</strong></td>
<td><strong>77</strong></td>
</tr>
</tbody>
</table>

---

Although these numbers are consistent with a 15-min terminal component, they do not allow for air traffic delays or circuitry due to terminal approach and departure procedures. As discussed later, airline operating policies determine the difference between the manufacturer's block time that reflects the capability of the aircraft and the airspace system, and a scheduled block time posted in a computerized reservation system. This seems to be particularly true for aircraft operators who may adjust scheduled block time to maximize on-time performance for purposes of marketing.

Establishing a basis for predicting tilt-rotor fares is more difficult. Text table (b) shows the approximate operating costs for a 31-seat aircraft, based on a 200 n mi stage length (from the NASA 1989 draft).

<table>
<thead>
<tr>
<th></th>
<th>$/Seat</th>
<th>$/Block Hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crew</td>
<td>2.5</td>
<td>85</td>
</tr>
<tr>
<td>Fuel</td>
<td>4.5</td>
<td>150</td>
</tr>
<tr>
<td>Maintenance</td>
<td>22.0</td>
<td>740</td>
</tr>
<tr>
<td>Indirect operating cost</td>
<td>13.0</td>
<td>440</td>
</tr>
</tbody>
</table>

Since indirect operating cost (IOC) includes a large number of components that depend on factors other than the aircraft type and block times, the above value is likely to be sensitive to assumptions regarding such factors as aircraft utilization and load factor. Note the unusually high maintenance forecast. Maintenance costs of this magnitude would probably be unacceptable to traditional operators of fixed-wing equipment who might expect reliability problems unless the tilt rotor is able to deliver fixed-wing standards of safety, reliability, and maintenance.

Text table (c) shows predicted total operating costs (1986 dollars per trip) from the 1989 NASA document.

<table>
<thead>
<tr>
<th>Stage Length (n mi)</th>
<th>200</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 seat (CTR-1900)</td>
<td>887</td>
<td>1551</td>
</tr>
<tr>
<td>31 seat (CTR-22A)</td>
<td>1446</td>
<td>2605</td>
</tr>
<tr>
<td>39 seat (CTR-22C)</td>
<td>1543</td>
<td>2722</td>
</tr>
</tbody>
</table>

The figures for the 31-seat tilt rotor are somewhat higher than those quoted in the FAA/NASA/DoD report. The figures given in the draft NASA document do not include aircraft ownership or lease costs (depreciation, financing, and hull insurance).

Comparative figures are also given for hypothetical turboprop aircraft. Total operating costs (1986 dollars per trip, including depreciation, financing and insurance) are given in text table (d) as:

<table>
<thead>
<tr>
<th>Stage Length (n mi)</th>
<th>200</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 seat</td>
<td>695</td>
<td>1377</td>
</tr>
<tr>
<td>39 seat</td>
<td>1215</td>
<td>2382</td>
</tr>
</tbody>
</table>
These two sets of figures are not directly comparable without adjusting the tilt-rotor figures for ownership costs. For the turboprop aircraft, these were $53.50 per million dollars of purchase price for a 200 n mi stage length, and $118 per million dollars for a 500 n mi stage length. Purchase price for the tilt rotor has been estimated as 50 percent more than a turboprop of equal capacity. Using the purchase prices given for the hypothetical turboprop aircraft in the NASA document, this would give a purchase price of $4.7 million for a 19-seat tilt rotor and $9.1 million for a 39-seat model (1986 dollars). These values appear to be too low. The V-22 price was recently estimated at $20–23 million per unit and climbing (Air & Cosmos, 1989), whereas Bell has estimated the cost of a 30-passenger civil tilt rotor at $18 million in 1986 dollars (Interavia, 1989). Aircraft purchase costs are generally not quite linear with size. The data for turboprop aircraft suggest a relationship of (seats)**0.87. However, tilt-rotor aircraft may not be able to achieve similar economies of size, due to the reduction in the size of the potential market for larger models and the engineering challenge of the larger rotor systems. Using the Bell figure of $0.6 million/seat, and assuming that purchase cost is linear with size, tilt-rotor ownership or lease costs (1986 dollars per trip) would be as shown in text table (e).

<table>
<thead>
<tr>
<th>Stage Length (n mi)</th>
<th>200</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 seat (CTR-1900)</td>
<td>610</td>
<td>1345</td>
</tr>
<tr>
<td>31 seat (CTR-22A)</td>
<td>995</td>
<td>2195</td>
</tr>
<tr>
<td>39 seat (CTR-22C)</td>
<td>1252</td>
<td>2761</td>
</tr>
</tbody>
</table>

Total operating costs (1986 dollars per trip), including ownership costs, would therefore be as shown in text table (f):

<table>
<thead>
<tr>
<th>Stage Length (n mi)</th>
<th>200</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 seat (CTR-1900)</td>
<td>1497</td>
<td>2896</td>
</tr>
<tr>
<td>31 seat (CTR-22A)</td>
<td>2441</td>
<td>4800</td>
</tr>
<tr>
<td>39 seat (CTR-22C)</td>
<td>2795</td>
<td>5483</td>
</tr>
</tbody>
</table>

Tilt-rotor total operating costs are thus approximately 2.3 times turboprop costs, over a range of stages and vehicle sizes.

We must point out that serious efforts are under way by NASA, Boeing Commercial Aircraft, and the Bell-Boeing team to rethink some aspects of tilt-rotor predicted operating costs, particularly propulsion system maintenance forecasts that are derived from helicopter maintenance data. Cost estimates are still a moving target, and it is not yet possible to establish a cost ratio with great precision. Assuming that fares were set to just recover total operating

---

3 The possibility of replacing the V-22's composite fuselage shell with an aluminum structure is being considered, as well as the weight savings associated with designing for a civilian rather than military mission. The additional weight and cost of noise and vibration control systems are not yet known.

4 The February 1991 NASA-FAA report confirms these observations. Projected maintenance costs are now estimated to be approximately 30 percent higher than those for a turboprop in the same service, and tilt-rotor operating costs (less ownership) are estimated to be 15 percent greater than for the corresponding turboprop. Furthermore, the tilt rotor's selling price, apparently based on market worth, is estimated at $430,000/seat for a 40-passenger vehicle. These estimates arrived too late to be included in our analysis.
and ownership costs, and an average load factor of 65 percent was achieved, the yield per revenue passenger mile (1986 cents) for tilt-rotor service would have to be as shown in text table (g).

<table>
<thead>
<tr>
<th>Stage Length (n mi)</th>
<th>200</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 seat (CTR-1900)</td>
<td>53</td>
<td>41</td>
</tr>
<tr>
<td>31 seat (CTR-22A)</td>
<td>53</td>
<td>41</td>
</tr>
<tr>
<td>39 seat (CTR-22C)</td>
<td>48</td>
<td>38</td>
</tr>
</tbody>
</table>

If the total operating costs are linear with stage length, the yield relation may be represented by:

\[ Y = a + \frac{b}{SL} \]

where \( Y \) is the average yield in 1986 cents per RPM and \( SL \) is the stage length in nautical miles. Text table (h) gives values for the parameters \( a, b \).

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 seat (CTR-1900)</td>
<td>33</td>
<td>4000</td>
</tr>
<tr>
<td>31 seat (CTR-22A)</td>
<td>34</td>
<td>3700</td>
</tr>
<tr>
<td>39 seat (CTR-22C)</td>
<td>31</td>
<td>3400</td>
</tr>
</tbody>
</table>

**Fixed-Wing**

Fixed-wing air travel times and average yields in specific markets can be obtained from published schedules and airline reported data. Recent (1987) values for the selected markets served from NY/NJ airports were used to estimate turboprop fare levels. See Table B.3 for fixed-wing fares, flight times, and estimated delays, and estimated tilt-rotor block times and fares. Moreover, it should be noted that airline fares are responsive to competitive effects, and could be reduced in high fare markets if a new service begins to erode an established airline’s market share.

Since tilt-rotor fare levels used in the analysis must necessarily be based on estimates of total operating costs, it may be argued that comparative fixed-wing fares should also be cost-based rather than determined by the current market levels. Existing fares may be set higher than levels strictly necessary to recover costs, and could be reduced if tilt-rotor service begins to divert traffic. The difficulty with such an approach is that it would require assumptions to be made about changes in load factor, which in turn depend on the type of equipment used, the service frequency, and fare discounting policies. To make assumptions about these factors in a systematic way would require a complex model of airline decisionmaking, which is beyond the scope of this study. However, to understand the extent to which existing fare levels in short-haul markets appear to con-
form to total operating costs, commuter airline operating costs were analyzed. The analysis suggests that 1987 commuter yields were in the range of 30 to 70 cents/mile, with a general trend line decreasing from 45 cents/mile at a 100 n mi stage length to about 25 cents/mile at a 300 n mi stage length. These quantities are consistent with the 19-passenger turboprop operating costs cited in the NASA draft study at a load factor of 65 percent.

**Commuter Pricing and Operating Policy**

It is difficult to define a ticket pricing and operating strategy for commuter operators because the entire regional airline industry is undergoing radical transformation. Regionals codeshare, and some are operated as subsidiaries of major air carriers. Acquisition is intended to produce an integrated multilevel network of cities, equipment, and schedules that assigns to commuter aircraft the primary role of connecting with the banks of arriving and departing jet aircraft at hub cities. The goal of commuter subsidiaries is to "feed" the hub, and in this way to enlarge the market share area and revenues of the major carriers. Even for commuters that code share but are not owned by a major airline, there are obvious pressures to concentrate their resources on feeding hubs rather than providing service between smaller metropolitan areas.

For a commuter airline owned by a major carrier, the business goal is not ambiguous: to provide service that maximizes the total of net revenues for the parent major that can be attributed to commuter operations plus the difference between direct commuter revenues and expenses.

Given the historical tradition of financially tenuous short-haul operations, we speculate that for the "captive" commuter operator, this ultimately reduces to employing their resources to increase parent company ticket revenues attributable to commuter operations. This may mean that otherwise profitable service may be eliminated in favor of using scarce resources (aircraft and personnel) to better serve hubs. Command Airlines, for example, served White Plains until quite recently, but it relinquished these operations after it became an American Eagle subsidiary of American Airlines, in order to concentrate on AA hub service.

Not only is commuter ticket pricing made more complex by the integration of commuter operators within a larger system, but also the analysis of modal choice as it is influenced by ticket price. A traveler who departs from a commuter destination, say Albany, and uses Port Authority airports (say, JFK) to connect to national or international destinations is not quoted a fare for the commuter segment and may not even be aware of the portion of the total fare due to the Albany-JFK leg. Thus, the Albany-JFK ticket price plays a major role in decisions between alternatives mainly for the non-connecting commuter passengers.

For analytic purposes, we will assume that commuter travelers, say between Albany and one of the three Port Authority airports, are influenced in their decisions about tilt-rotor and fixed-wing service only by fare, service, and schedule differences associated with the Albany-NY portion of a journey, and that factors such as airline preference, frequent flyer program, and the service and costs for the other segments of a journey are identical for both tilt-rotor and fixed-wing choices.

There is no database for tracking commuter delays and on-time performance, although individual operators are likely to maintain their own records. As we noted earlier, scheduled block times are related to both aircraft performance and to the scheduling philosophy of the operator.

A wide variety of commuter equipment is used by individual operators, ranging from unpressurized and slow Shorts to more advanced ATRs, Saabs, and Dash-Eights. Over time,

---

5This analysis is available upon request from the authors.
we anticipate the average size of commuter aircraft to increase, and fewer 19-passenger airplanes to be flying in the Northeast. Furthermore, the range in amenities and performance is likely to narrow at relatively high levels.

Today, one commuter operator's flight between Albany and JFK could be scheduled for an hour and a half using a slow-moving older Short, while another operator will schedule a 30 percent shorter elapsed time using more modern equipment. However, neither equipment nor time of day can adequately explain the surprisingly large differences in scheduled elapsed time, confirming that operating philosophy and the desire to maintain on-time performance are important. Other factors with regard to commuter operations are a willingness to cancel late flights if there are a number of closely spaced departures, and "captive" commuter operators at a hub airport who may sacrifice on-time performance by deferring to waiting larger aircraft operated by the parent carrier.

Local Travel

The travel time and cost for airport and vertiport access trips depend on the mode used. At the origin end of the trip, it is likely to be private automobile. At the destination end of the business trip, it is likely to be taxi or rental car.

Private automobile costs can be based on mileage rates plus an allowance for parking at the airport or vertiport. A 1978 air passenger survey indicated that 75 percent of passengers on business trips to or from the New York area using JFK with destinations within 500 miles had a trip duration of less than five days, suggesting an average parking duration of between three and four days. Parking rates depend on the lot used—parking duration data for JFK indicate that about 45 percent of those parking for three days use the long-term lots, rising to about 50 percent of those parking for four days (Gosling, 1984a). Parking rates are higher at La Guardia and Newark than at Kennedy, and La Guardia does not have a long-term lot. Based on the 1987 parking rates for the NY/NJ airports, this suggests a typical parking cost of $35. Parking is likely to be less expensive at smaller airports, perhaps around $20.

The choice of taxi, limousine, rental car, or other means in the destination city is likely to be influenced by trip purpose and the distance from the airport to the final destination, as well as the duration of the trip and the destination location within the metropolitan area. Taxi rates vary from city to city, with typical values in 1987 of a flag drop of $2.00 and 14¢ per tenth mile. Since most rental car use is charged by the day rather than by distance, the costs are not particularly sensitive to the locations of final destination or airport/vertiport. Rental rates depend on the size of car and corporate discounts, but typical values in 1987 might be around $35 per day; costs for gasoline would have been around 5¢ per mile. For multiday trips, how much of the rental costs should be allocated to the air trip is a difficult question, since the car is likely to be used for other purposes during the trip. For the analysis, the local travel cost at the destination end of the trip was based on the minimum of the round-trip taxi fare between the airport/vertiport and final destination or two days' car rental plus gasoline cost.

Simulation of Market Dynamics

The fare offered in any market is a function not only of the trip length but also of the market density. The denser the market, the larger the aircraft that can be used, reducing seat-mile costs. Larger aircraft can also be used if flight frequency is reduced. However, such an action would open the market to competition from other carriers offering more frequent service with smaller aircraft, or would lead to loss of traffic to nearby airports where more
frequent service is available. To represent the effects of these market dynamics, the equilibrium fares and frequencies in a specific market can be determined by simulating the effect of varying fares and frequencies on operating economics.

Our analysis is intended to forecast tilt-rotor demand vs. demand for fixed-wing service between destination cities and all three Port Authority airports, treated as a single entity. A more detailed study would attempt to forecast demand at each of the three airports. Such a study would require far more detailed data about the patterns of airport-specific commuter operations and ridership than are generally available, as well as the operating and pricing strategies for each commuter airline.

**Airport Markets**

In general, tilt-rotor service must compete in airport-to-airport markets against conventional air service. Given the average daily traffic in the market, the frequency of tilt-rotor and fixed-wing service can be calculated by assuming that fixed-wing fares remain at current (1987) levels and the frequency for the fixed-wing service adjusts to maintain the current (1987) ratio of departures to traffic. Then, for any selected tilt-rotor frequency and fare, the mode choice model can be applied to determine the traffic for each service and the resulting tilt-rotor load factor and operating surplus or loss. If the tilt-rotor service experiences a loss, the fare and frequency are progressively adjusted to levels that eliminate the loss. If the service experiences a surplus, a new frequency and break-even fare can be calculated to maximize the traffic share or achieve a specified load factor.

**Vertiport Markets**

Again, the alternative to tilt-rotor service to or from vertiports is conventional air service between regional airports. It is assumed that tilt-rotor traffic from regional vertiports will not be sufficient to significantly affect fares or frequencies of the conventional air service. Using the vertiport access times within the catchment area served by the vertiport and the access time to the corresponding regional airport, the mode choice model is run to determine the proportion of the catchment area traffic that is attracted to the tilt-rotor service, and the resulting operating surplus or loss. The tilt-rotor service frequency and fare are then adjusted as before to determine the combination that maximizes the traffic volume, at break-even fares.

The proposed catchment area approach is open to a number of objections. First, it assumes that all travelers within the catchment area face an equal accessibility differential between the vertiport and the competing airport. This is clearly not the case, and at the boundary of the catchment area of the vertiport and that of the airport, the accessibility of the two will be the same. Further, the very concept of a “catchment area” is not really valid, since some travelers with trip ends close to the airport might choose to use a tilt-rotor service from a regional vertiport, perhaps because of schedule convenience or other reasons. However, the other simplifications of the analysis, such as ignoring variation in traveler income, trip purpose and trip duration, make this a reasonable approach, given the limited available data about commuter passengers who utilize Port Authority airports.

---

6Implicitly, this assumes that fixed-wing equipment would be no larger than today’s, given that average load factors are not likely to vary much over time. Another bounding approach is to assume that fixed-wing operations remain constant in number over time and that increases in passenger traffic are satisfied by larger turboprops. We have calculated demand using both sets of assumptions, but our detailed tables are based on the first assumption. Market share estimates for tilt-rotor service are not very sensitive to the choice of assumption.
Market Factor Scenarios

Since the analysis outcome depends on the values used for fares and travel times on competing modes, which themselves depend on factors that cannot be predicted with any accuracy, it would seem reasonable to prepare market share projections for a range of scenarios, reflecting the interaction of different values for these variables.

The fares charged for a specific air service depend not only on the cost of providing that service, but also on the pricing policies adopted by the operator. In the case of tilt-rotor service, there is considerable uncertainty over the likely capital costs of the vehicle, as well as some operating costs, particularly maintenance. Estimates of competing fixed-wing fares are also dependent on pricing policies, as well as such factors as the type of equipment used and the way that indirect operating costs are allocated to specific services and fare classes. Real average yields in the airline industry have been declining historically, although the last two years have seen a reversal of this trend, with annual increases of between 5 and 10 percent. It appears likely that this is a fairly short-term readjustment to the intense fare competition of the mid 1980s, and that the long-term trend (aside from oil shock effects) will be for yields to at least stabilize (in constant dollars) if not continue to reduce. Traffic growth should allow reduced yields in specific markets, as larger, more cost-effective equipment is used.

The linearity of the utility function in terms of fare simplifies sensitivity analyses. Our baseline case scenarios are based on projected tilt-rotor costs developed above and 1987 fares in each market for conventional fixed-wing service. We have also made several excursions from this case.

As remarked earlier, the substitution of tilt rotors for fixed-wing commuter aircraft operating between smaller cities and Port Authority airports could increase capacity at the Port Authority airports by partially freeing runways, gates, and slots for use by larger and longer-range jets. If this can be achieved while maintaining service to commuter destinations, then enplanements and perhaps even aircraft movements could be increased.

Airport operators, noncommuter airlines, and noncommuter passengers would be potential beneficiaries of this increase in capacity. An important related issue that bears on tilt-rotor market share is the nature of the benefits, if any, that commuter travelers could derive from airport-based tilt-rotor service, particularly when fixed-wing and tilt-rotor aircraft compete in the same market and passengers are free to select their preferred mode of service. Passengers choosing between tilt-rotor and fixed-wing service will weigh the perceived differences between two systems using a number of important criteria. For an airport-based system, only small savings in ground access time and access costs for tilt-rotor travelers may be expected, perhaps through more efficient terminal access. The time and costs of surface access to a terminal are likely to be the same for both systems unless incentives such as preferred parking and special discounts are brought forward to increase tilt-rotor ridership. This differs from an urban vertiport-based system where important savings in access time and costs are the primary benefits of tilt-rotor service.

If such incentives are not used and passengers are indifferent to intrinsic differences between comparably sized fixed-wing and tilt-rotor aircraft, then flight frequency, scheduled elapsed time, on-time reliability, and ticket price are the main determinants of modal choice.

Flight Delay: Data, Magnitude, and Source

To better assess trade-offs between the components of travel time and relative fares, it is necessary to understand the magnitude and sources of flight delay. Only in this way can the
potential of a tilt-rotor system to alleviate delays be evaluated. Ultimately, this potential must be translated into scheduled block times that are both realistic and can serve as marketing tools.

For turboprop commuter aircraft, the theoretical flight time, as suggested earlier, is about 80 percent of the scheduled block time for a nominal 200 n mi segment. However, some commuter airlines may schedule elapsed times that are substantially longer than this, based on historical data. The difference between the two times provides a small operating margin for accommodating delays that are airline related (crew, equipment, fuel, baggage, connecting flights, etc.) and delays that are system related. Different operators have different scheduling philosophies, some conservative and some less so. For example, some JFK-Albany flights are scheduled for one and one-half hours and some for 50 minutes elapsed time, depending mainly on the airline but also on equipment and time of day.

Some inferences concerning airline- and system-related delays may be made from Department of Transportation (DOT) and FAA data. The DOT data are collected from the largest U.S. carriers (each with greater than one percent of airline revenues) and are used to prepare a monthly consumer report. The report is intended to inform travelers about the quality of airline service, and includes measures of on-time performance and delay. Using the DOT's criteria, a flight is delayed if it arrives or departs more than 15 minutes after the scheduled time shown in a carrier's computerized reservation system. The scheduled block time is generally enough to accommodate some flight delay, and individual carriers can adjust schedules if their on-time ratings are poor. However, there are limits on the degree to which schedules may be stretched because flight crews must be compensated for extra time, and because aircraft utilization rates may drop if scheduled block times are too long.

By contrast, the FAA concept of delay is aimed at assessing the performance of the ATC system, including the effect of adverse weather, volume, system equipment failures, and congestion. For the FAA, delay is the deviation between the actual and the optimal flight time achievable in the absence of adverse weather, congestion, National Airspace System equipment outages, runway closures, etc. We judge that, in general, the DOT's on-time reporting system is a far more revealing measure of delay as it is experienced and perceived by passengers, despite the flexibility contained within airline schedules.

The FAA delay clock is set when the pilot requests permission to leave the gate. It is not based on scheduled departure time, and does not record delays within the purview of the pilot or the airline. Thus, an airplane that is late to depart and late to arrive may not be recorded as an FAA flight delay if its elapsed time is within the optimal range.

FAA delay data are gathered from two sources: the Air Traffic Operations Management System (ATOMS) that relies on reports from ATC facilities, and the Standardized Delay Reporting System (SDRS) that relies on reports from three carriers (American, United, and Eastern) comprising 25 percent of all air carrier operations. Although SDRS data may be qualitatively useful, the limited sample and the occasional large differences in performance between airlines weaken the applicability of SDRS data to the entire system. In addition, neither DOT nor FAA collects data on commuter performance that could be used to develop a realistic model of commuter flight delay. For ATOMS, only delays greater than 15 minutes are recorded, whereas all delays are noted by SDRS.

Given the striking differences between the DOT and FAA datasets in both their objectives and data sources, it is not surprising that large discrepancies exist in delay frequencies recorded by the two systems. The FAA data are likely to show both lower frequencies and smaller magnitudes than the DOT data. To illustrate, the 1988 FAA-ATOMS delay frequency
was 2.8 percent for all U.S. carrier flights, whereas the DOT delay frequency as measured by on-time arrivals was nearly 10 times greater. For large U.S. airports, DOT delay frequencies are about five times greater than the FAA's.

The DOT data do not include the sources of delay. The FAA collects such data and reports that adverse weather accounted for some 70 percent and increased terminal volume accounted for greater than 20 percent of delayed operations during the 1984–1988 period. The average SDRS-reported flight experienced about a 15-minute delay, with 80 percent of delay occurring during taxi-in or taxi-out. In general, both the FAA and individual airlines discourage the use of gate holds if system flow is limited, preferring to free gates for incoming or departing traffic.

Focusing on delay frequencies at the New York/New Jersey airports, 6.7 percent of Newark operations, 5.5 percent of JFK operations, and 5.3 percent of La Guardia operations were delayed by more than 15 minutes in 1988, according to the FAA. Using 1989 DOT data, estimated late arrival frequencies are considerably greater, or ~ 35 percent for Newark, ~ 33 percent for JFK, and ~ 40 percent for La Guardia. In terms of departures, estimated 1989 late departures are are ~ 28 percent of Newark flights, ~ 33 percent of JFK flights, and 30 percent of La Guardia flights. DOT's monthly consumer report also groups on-time performance data according to airline, time of day, and flight number. It is apparent, using the DOT data, that certain carriers, certain times of day, and certain flights often exhibit consistent patterns of delay. An extreme example occurred during December 1989, when one carrier was responsible for 60 percent of the 100 scheduled U.S. carrier flights with the poorest on-time frequency. For these 100 poorest performers, only 18 percent arrived on time, and the average delay per flight ranged from one-half hour to over an hour.

As earlier noted, the DOT does not gather data from commuter operators, the FAA-ATOMS summary does not present data in a sufficiently detailed form to delineate commuter delays, and the SDRS data cover only three major carriers. Thus, there is little empirical support for statements about the performance of commuter carriers. Despite data limitations and the lack of adequate analysis of existing data, we can make a number of preliminary observations.

- Flight delay experienced by passengers is due to a combination of system-related and airline-related effects. We believe that data are collected that could better define the two sources of delay, but they have not been analyzed in a way that clarifies how system performance events actually influence on-time performance.
- System delays, about 70 percent due to adverse weather and over 20 percent due to volume effects, are far less frequent than airline-related delays. The New York airports are not considered to be unusually weather-sensitive. In terms of on-time performance, en-route delays are smaller in magnitude than delays in departure time.
- FAA delay estimates are likely to markedly underestimate the magnitudes that are experienced by air travelers.
- Shuttle flights between two cities show better on-time performance than flights involving several segments.
- We speculate that the frequency and magnitudes of commuter delays are not likely to be superior to that of major carriers, and that flight cancellations are more frequent. In addition to airline-related causes stemming from crew, fuel, baggage, equipment, and boarding difficulties, commuter operators are more susceptible to delays associated with connecting flights. Commuter operators, because of the limited slack in aircraft schedules, may cancel overly late flights rather than permit them to arrive several
hours late. Under some circumstances, commuter operators may delay departures to give priority to larger equipment operated by the parent major carrier.

We can only speculate about the cascade of delays whose cumulative impact results in substantial deviations between actual and scheduled performance. Weather-associated delays and related traffic volume effects on ATC operations could produce prolonged taxi-out times at one airport that would, in turn, trigger delayed arrivals and departures at all subsequent destinations. In these instances, passengers at a number of airports would experience long delays, but only the first delay would be noted by the FAA and attributed to a system difficulty.

How do these data, fragmentary as they are, affect our analysis? We judge that all-weather tilt-rotor performance is necessary but not sufficient to ensure a desirable level of on-time performance. Further, a tilt-rotor ATC system should operate independently of the system for fixed-wing aircraft if tilt rotors are to approach their potential. Even then, on-time performance is still strongly influenced by pilot and carrier decisions, in addition to adverse weather and other system problems. Accordingly, tilt-rotor operators will have to pay far greater attention to on-time performance if tightly scheduled block times are to be taken seriously by travelers. If airline or pilot decisions are responsible for a significant fraction of all flight delays, the problem is partially correctable.

In terms of our demand analyses, the cumulative uncertainty in causes and magnitudes of delay, particularly for commuter flights, implies that our modal choice analyses should consider two bounding cases. These cases are defined in the next section.

Travel Time Advantage

Tilt-rotor travel time advantage can arise through avoiding increases in delays experienced by fixed-wing aircraft, or shorter access and terminal processing times due to the location or size of vertiports or tilt-rotor terminals. Future levels of air traffic delay at the NY/NJ airports will depend not only on the growth and composition of traffic using the airport, but also on the effect of capacity enhancement measures taken in the meantime. The FAA’s Airport Capacity Enhancement Plan (FAA, 1989) predicts between 50,000 and 75,000 hours of delay per year at Kennedy and La Guardia airports by 1997, and between 75,000 and 100,000 at Newark, if no actions are taken to increase capacity, or between 8 and 14 minutes per operation. However, using average delay values obscures important variation, both between airports and across individual flights. Differences between the three airports are shown in Table 5, together with recent trends in the percentage of operations delayed by more than 15 minutes. Although extrapolation of the average delay per operation beyond 1995 is somewhat conjectural, Fig. 40 shows the result of applying the delay estimation methodology adopted in earlier editions of the Airport Capacity Enhancement Plan (FAA, 1987) to forecast traffic levels at Kennedy and La Guardia, assuming no increase in capacity during the period. The potential delay reduction from various capacity improvements identified by airport capacity enhancement task forces at Kennedy and La Guardia are shown in Table 6. Some of these measures appear to significantly reduce delays, but it is not clear to what extent gains from one measure will reduce the benefits from others, and thus the reductions can be aggregated. Of course, not all these proposed improvements may be implemented (particularly the proposed new runway

---

As noted in the preceding subsection, there are serious limitations on the FAA's approach to estimating delay. The FAA may in fact markedly underestimate delays as they are experienced by travelers since forecasts are likely to reflect the FAA's restricted focus on delays that are directly attributable to system performance. Nevertheless, FAA's forecasts are useful for calibrating the relative degrees of congestion that are likely to occur.
Table 5
AIRCRAFT DELAY TRENDS AT THE NY/NJ AIRPORTS

<table>
<thead>
<tr>
<th>Year</th>
<th>Kennedy</th>
<th>La Guardia</th>
<th>Newark</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hours of Air Carrier Delay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1984</td>
<td>42,600</td>
<td>48,800</td>
<td></td>
</tr>
<tr>
<td>1985</td>
<td>21,242</td>
<td>37,062</td>
<td>50,359</td>
</tr>
<tr>
<td></td>
<td>Percentage of Operations Delayed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 minutes or more</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1984</td>
<td>12.3</td>
<td>14.5</td>
<td>10.6</td>
</tr>
<tr>
<td>1985</td>
<td>6.1</td>
<td>9.2</td>
<td>9.2</td>
</tr>
<tr>
<td>1986</td>
<td>7.0</td>
<td>8.9</td>
<td>13.8</td>
</tr>
<tr>
<td>1987</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>1988</td>
<td>5.3</td>
<td>5.2</td>
<td>6.7</td>
</tr>
</tbody>
</table>

*Estimated from average delay per operation.

at JFK), while others may be identified in the future, or unforeseen changes may occur. However, even under worst-case conditions of no capacity improvement, the average delay per operation does not appear to increase beyond about 10 minutes, with relatively small differences between 1995 and 2005.

Therefore, two bounding travel time advantage scenarios have been defined. The baseline scenario assumes that the tilt rotor will have an advantage of 15 minutes over conventional air service, reflecting both air traffic delays and terminal access and processing times. In the Boston and Washington markets, the advantage is increased to 30 minutes, reflecting both the more severe congestion at those airports and the potential terminal and processing time advantages at both ends of the trip. The other scenario assumes that tilt-rotor operations will not lead to a significant improvement in actual or scheduled block times.

Choice Model Sensitivity

In addition to considering the effect of changes in the input variables to the mode choice model, the sensitivity of results to changes in parameter values should also be considered.

Value of Travel Time. The parameters adopted for the mode choice model imply a specific dollar value for travel time. However, as noted above, this ignores such issues as the variation of the value of time across different travelers, such as those with higher incomes or those traveling on business. There may well be a large enough number of travelers with a high enough value of time to support tilt-rotor service, although at the average value of time, such service would not be viable. Furthermore, as incomes rise in real terms over time, it may be expected that the perceived value of time will also increase.

To assess the sensitivity of the results of the analysis to these factors, the analysis was repeated with an implied value of time of both $25 and $50 per hour. The higher value is similar to one derived by Morrison and Winston (1989) from an econometric analysis of air traveler choice. It is significantly larger than the values that frequent flyers admitted they were willing to pay, based on our 1989 focus groups and Albany survey results.
Mode-Specific Constant. The mode-specific constant for tilt-rotor service expresses how travelers perceive the service compared to conventional fixed-wing air service if fares and flight times are the same. It has a significant effect on the results of the analysis, as noted above. Therefore it appears reasonable to consider a range of possible values. In the case of competition with jet service, if tilt-rotor aircraft are perceived as having no intrinsic disutility, the mode-specific constant would be 0.0. As noted earlier, it seems implausible that a 31-seat rotorcraft would be viewed as no different from a 120- to 150-seat jet aircraft, and thus an upper bound of −0.5 may be plausible. On the other hand, if tilt-rotor service were considered less desirable than commuter turboprop (≤ 30 passenger) service, the constant would be less than −1.5. A value of −2.5 might be a lower bound, although this is admittedly speculative.

In the case of direct competition with commuter turboprop service, the baseline case should use a mode-specific constant corresponding to no perceived differences, assuming that travelers are not intrinsically averse to tilt-rotor equipment.
Table 6
DEPRESS REDUCTION FROM POTENTIAL CAPACITY ENHANCEMENT MEASURES

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kennedy International Airport</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allow Class 3 and 4 aircraft departures on runway 31R</td>
<td>3,967</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allow Class 2 quiet jet departures on runway 31R</td>
<td>6,933</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Develop independent converging IFR approaches to runways 13R and 22L</td>
<td>1,800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relocate runway 4L glide slope and develop staggered approaches to runways 4L/4R</td>
<td></td>
<td>9,233</td>
<td></td>
</tr>
<tr>
<td>Short runway 4/22E for general aviation aircraft</td>
<td></td>
<td>11,200</td>
<td></td>
</tr>
<tr>
<td>Short (shoreline) runway 13/31S for general aviation aircraft</td>
<td></td>
<td>8,350</td>
<td></td>
</tr>
<tr>
<td>Full-length (shoreline) runway 13/31S for all aircraft departures</td>
<td></td>
<td></td>
<td>18,717</td>
</tr>
<tr>
<td><strong>La Guardia Airport</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduce longitudinal separation to 2.5 n mi for IFR arrivals</td>
<td>4,717</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install state-of-the-art radar</td>
<td>5,100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eliminate noise restrictions on runway 13 departures</td>
<td>497</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relieve airspace interaction between LGA runway 22 and JFK runway 13L</td>
<td>567</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


SCENARIO ANALYSIS

In conducting the scenario analysis, it is not necessary to examine every combination of all the above assumptions. Since the implied value of time determines the substitution rate between fare and travel time that produces no effect in the market share, any change in one variable can generally be expressed as an equivalent change in another. However, some of the scenarios, such as the travel time advantage, apply a constant change to all markets, while for other scenarios the change in a given variable will vary across markets.

For the initial sensitivity analysis, tilt-rotor market shares were estimated, using both the low and high value of time and mode-specific constants of 0.0 and –1.5. As noted, we also considered the situation where scheduled air travel times are equal for both tilt-rotor and fixed-wing equipment. However, our baseline case assumes that scheduled tilt-rotor flight times are shorter than for corresponding fixed-wing equipment, as shown in Table B.3.
IX. MARKET DEMAND ANALYSIS: FORECASTS

SCREENING ASSUMPTIONS

Increasingly realistic analyses were made to grasp the quantitative and qualitative implications of the model and to guide forecasts.

For preliminary screening purposes, the percentage of traffic in each market that might be attracted to airport-based tilt-rotor service was initially estimated using the market share analysis model, assuming equal frequency of tilt-rotor and conventional air service, with tilt-rotor fares based on breaking even at a 65 percent load factor. Conventional air service flight times and fares were based on 1987 values for each market, with tilt-rotor costs adjusted upward by 8 percent from their estimated level in 1986 dollars. In addition to differences in scheduled flight time, the tilt-rotor service was assumed to experience a travel time advantage of 30 minutes in the case of Boston and Washington, and 15 minutes for other markets, to account for increased air traffic delays for conventional air service and ground access time savings as discussed in Sec. VIII and shown in Table B.3. This approach provides a preliminary indication of potential tilt-rotor markets equivalent to assuming that increased demand is met mainly by increasing the frequency of service. A more realistic assumption is that increased demand is met by increasing aircraft size, while maintaining a more or less fixed frequency of flights. It can be shown that tilt-rotor market share is not sensitive to the precise way that increases in demand are met, given that the schedule frequency term in the utility formulation approaches its limiting value.

The sensitivity of these results to the assumed parameter values of the modal choice model was investigated by varying the mode-specific constant and value of travel time. As would be expected, the tilt-rotor share of the markets increases significantly at higher values of travel time and lower perceived tilt-rotor disutility. The number of markets with tilt-rotor share exceeding 20 percent increased from five under the least favorable assumptions ($a_0 = -1.5, a_1 = -0.04$) to 46 under the most favorable assumptions ($a_0 = 0, a_1 = -0.02$).

However, the two assumptions of equal frequency and 65 percent tilt-rotor load factor are clearly inconsistent for many markets. The inconsistency results in tilt-rotor load factors that are sometimes too large, particularly for highly seasonal markets such as Cape Cod where we have underestimated average annual movements by using the March Official Airline Guide (OAG) schedule. Therefore a more comprehensive calculation was performed, using the market dynamics simulation approach discussed in Sec. VIII.

Airport Market

Our first set of market dynamics simulations was based on unconstrained load factors. No explicit allowance was made for submarkets that might be served by potential vertiports in either the origin or destination region. In addition, competitive conventional air service was assumed in all markets. Conventional air service frequency was determined by assuming a constant number of passengers per departure in each market, based on the 1987 traffic, allowing for diversion of passengers to tilt rotor. The number of passengers per departure in each market was determined by adjusting the average daily frequency in the market given by the March 1989 OAG to 1987 levels based on the change in traffic at the three NY/NJ airports between the two periods. The market dynamics simulation showed that, in general, increasing
the frequency of tilt-rotor service reduced the break-even fare. However, the combination of higher frequency and lower fares naturally attracted more traffic, and load factors therefore increased. The traffic that tilt-rotor service can attract therefore depends on selecting an acceptable upper load factor limit. This is a complex question that is influenced by considerations of traffic variation over the day and week, aircraft utilization, and yield management strategies. Since deregulation, the U.S. domestic airlines have been unable to achieve average load factors much above 65 percent, except during peak periods, when levels as high as 75 percent have been achieved by some carriers. The nature of the tilt-rotor service may permit somewhat higher load factors than the industry average, but mean levels above 80 percent would be highly implausible. The choice model used in the analysis is elastic with respect to fares, so increasing fares to reduce load factors results in revenue falling faster than traffic, and consequent uneconomic operations. Thus, the only options when break-even load factors are too high for viable operations are to reduce frequency or subsidize the service.

For the case of unconstrained load factor, markets that appear able to support tilt-rotor service at 1995 traffic levels (without subsidy) are led by Boston and Washington, which appear able to support between 15 and 30 flights per day in each direction, depending on the average load factor that can be achieved. Potential secondary markets capable of supporting three or more flights per day include Albany, Baltimore, Portland, Providence, and Worcester, although none seemed able to support more than five flights per day without exceeding an 80 percent average load factor. Hyannis may be able to support two flights per day. Using a 75 percent load factor as an upper bound, the 1995 potential tilt-rotor market is approximately 70 flights per day in each direction, including 50 for the Boston and Washington markets.

Applying the analysis to the projected 2005 traffic did not change the results significantly. The number of daily operations in each market for a given load factor increases somewhat, as might be expected, but no important new markets emerge.

Next, we examined the implications of limiting the load factor to 65 percent and varying price. Subsidizing tilt-rotor operations (or increasing landing fees for fixed-wing aircraft) would obviously increase both the number of potential markets and the viable tilt-rotor frequency in each. The more realistic load factor reflects the political difficulty that would arise from subsidizing what is still premium service and may not be available to many potential users. A subsidy of $25 per passenger would permit limited tilt-rotor service to Hartford, Manchester, Philadelphia, and Syracuse, as well as increasing service in other potentially self-supporting markets to about 130 flights per day each way. We also studied the case where tilt-rotor and fixed-wing flight times are equal. The modal share analyses were then modified using data and judgments about competing surface modes and connecting passengers to refine our forecasts. The refinements invariably led to a decrease in tilt-rotor market share.

**Vertiport Markets**

The methodology used for the airport markets can also be applied to the vertiport markets, with appropriate adjustments to the delay/access time penalties to reflect the accessibility advantages of the vertiports. An important new parameter is the fraction of the total market included in the catchment area associated with each vertiport. As described in Sec. VII, the submarket for a site located in mid-town Manhattan is 25 percent of the total. The linearity of the utility function in terms of access times and costs permits the analysis to be performed using differences rather than absolute values. To illustrate, we employed a difference in ground transportation times of 45 minutes, terminal transit times of 10 minutes, and ground
access costs of $14, all in favor of the tilt rotor. As in the airport-to-airport case, the modal forecasts were then modified for competing surface modes and connecting passengers.

MARKET SHARE ANALYSIS RESULTS

We next summarize the results we obtained for the projected growth of tilt-rotor markets in the area served by the Port Authority of New York/New Jersey. The formal predictions of the modal share analysis have been modified by data and judgments about fares, passenger attitudes, surface modes, and the proportion of commuter travelers who use Port Authority airports for connecting flights.

Our market share analysis is based on a mathematical model widely used in empirically based demand analysis of aviation and other transportation systems. The model attempts to reflect the value (utility) that passengers ascribe to such factors as aircraft size, type (commuter vs. jet), schedule frequency, average fare, travel time including delays, and ground transportation costs, based on their actual behavior rather than on their stated preferences. It simulates aggregate market dynamics by calculating the aggregate number of tilt-rotor and fixed-wing flights from all Port Authority airports, treated as a single entity, needed to accommodate the projected traffic. The parameters of the model are adapted from values used by others after analyzing a wide range of datasets. Since no single dataset corresponds closely to the tilt-rotor case, we have selected parameter values on the basis of available data, sensitivity analyses, and judgment. An important side issue is that few solid data are available regarding the characteristics of commuter passengers, in particular the fraction for each important commuter city that uses Port Authority airports to connect with international or domestic flights. Resolving this uncertainty would be necessary to determine accurately the number of commuters who could not benefit directly from a Manhattan vertiport.

For potential passengers, decisions about choosing tilt-rotor service pose a trade-off between time and money, provided that civil tilt rotors are generally regarded as safe, reliable, and no less attractive than the large commuter aircraft that are likely to be available in the 1995–2005 frame.

An estimate of the dollar value of time is thus a significant parameter that needs to be folded into any systematic estimate of market share. On an aggregated basis, the available historical data, after econometric analyses of traveler choice, reveal that the value of time should be bracketed between $25 and $50 an hour, in 1987 dollars. We feel compelled to chose the lower value for our baseline forecasts, because the focus groups (business travelers) and our survey of Albany commuters both demonstrated that travelers, when queried, were not willing to pay more than $15 or $20 an hour for travel time savings. However, we performed forecasts using both $25 and $50, noting that the $50 an hour rate could apply to certain high-value submarkets. It could also reflect a more positive attitude about the technology or an aversion to fixed-wing congestion.

We considered three baseline scenarios:

a. Tilt rotors substitute for conventional (1995–2005) fixed-wing commuter airplanes, and land and depart at existing Port Authority airports. If the entire system including the infrastructure is properly configured and used by an appreciable number of passengers, then the burden of commuter movements at New York airports could be reduced, freeing commuter slots for other purposes. Prerequisites are that tilt-rotor operations can be positioned at existing airports and that tilt-rotor air and ground...
movements can be separated from fixed-wing traffic without any time penalty against tilt rotors.

b. A new vertiport is constructed in midtown Manhattan to serve travelers to and from airports in markets that appear most promising for supporting scheduled tilt-rotor service. The most promising cities are Boston and Washington, although service between Manhattan and cities that are now served primarily by commuter carriers is also analyzed. An important trade-off here is that the limited capacity of tilt-rotor aircraft compared to the jets that connect New York with Boston, Washington, and other major cities implies that three to five tilt-rotor flights on average are required to supplant one typical shuttle flight.

c. A series of vertiports is established in each submarket within the entire region served by the Port Authority. These vertiports offer potential travel time advantages, compared to using Newark, La Guardia, or JFK. We forecast the aggregate number of travelers who could be attracted to such a system, with suitable but unspecified vertiport locations within each submarket. Our analysis of this scenario should be compared with the corresponding analysis in the Port Authority tilt-rotor study performed by Hoyle, Tanner, and Associates, 1987. The analysis of this scenario is based on an aggregated (top-down) view of the competition between fixed-wing service at Port Authority airports and tilt-rotor service provided at regionally dispersed vertiports.

Scenario a

Scenario a involves tilt-rotor-commuter aircraft competition at existing Port Authority airports modified for tilt-rotor service and with appropriate provisions for effective tilt-rotor air traffic control. We have performed a (bottom-up) city-by-city analysis of tilt-rotor market share, based on the hypothesis that tilt rotors would operate and be controlled by the FAA in a way that would exempt them from most air traffic delays encountered by fixed-wing aircraft. We quantify this hypothesis by assigning scheduled block times for tilt-rotor aircraft derived from theoretical block times. For fixed-wing craft, we assign a point-to-point time that results from adding 30 minutes (for Boston and Washington) or 15 minutes (for other candidate cities) to scheduled flight times in the 1987 OAG. To illustrate, for Washington, D.C., the assumed tilt-rotor time is 0.78 hr and fixed-wing time is 1.75 hr; for Albany, tilt-rotor time is 0.67 hr and fixed-wing time is 1.25 hr; for Buffalo, tilt-rotor time is 1.09 hr and fixed-wing time is 1.43 hr, etc.

Figure 41 is a general curve demonstrating the relationship between market share and the average fare difference between tilt-rotor and fixed-wing commuter service. We use the term average because our fares do not account for discounts, restrictions, and promotional fares, except in an aggregated way. Figure 41 follows from a market share analysis for each city where commuter carriers provide service. The curve is shifted to the left by about $12–$14 when tilt-rotor scheduled flight times are identical to those for fixed-wing service.

From Fig. 41, the detailed analyses upon which it is based, and Table 6, we estimated the tilt-rotor market share for service provided between Port Authority airports and the most promising cities with substantial commuter service. Providence, Philadelphia, Albany, Hartford, Worcester, Manchester, Baltimore, and Atlantic City were considered, as well as a number of other cities that did not meet our screening criteria of 100,000 passengers in 1995, but appeared capable of supporting two round-trips per day of our canonical assumed 31-
passenger vehicle. We considered a number of pricing strategies, and employed $25/hr and $50/hr as the travelers’ value of time. If the tilt-rotor fare premium were set to permit break-even operations for each route (and the fixed-wing price is set at its market-driven 1987 level), then tilt-rotor commuter service could capture 25 percent of all commuter passengers; if the fare premium were a uniform $30, it could capture 27 percent of commuter passengers; and if
the fixed-wing fare covered only costs and both services operated break-even, then the tiltrotor market share would be 11 percent or even less. We note that our estimate of the necessary fare premium in the latter instance may not be sufficiently high, given the tilt-rotor cost estimates in Sec. VIII. We have used only a factor of two in estimating the break-even fare premium, rather than the full factor of 2.3 for the relative cost ratio between tilt rotor and turboprop. Thus, the 11 percent market share could drop even further, to perhaps 5 percent or less, if fixed-wing fares were set aggressively. Furthermore, we assumed that tilt rotors would be able to operate far more efficiently with regard to air traffic control and flight schedules than fixed-wing aircraft.

We have also assumed that passengers would continue to be indifferent to the type of commuter aircraft, as suggested by some of our focus group respondents, and that they would also be indifferent to the perceived difference between tilt rotors and comparably sized turboprop aircraft. Thus, commuter tilt-rotor service that offered no direct travel time advantage would be selected on the basis of fare alone if passengers were given the opportunity to choose their service.

In our forecasts for the case where tilt rotors offer no scheduled flight time advantage, the tilt-rotor market shares are approximately halved. This underscores the significance of FAA and airline policies that permit tilt-rotor aircraft to operate close to their full potential. Time saved is time saved, and our modal share forecast is based on the empirically derived concept that time savings translate into fare differences.

Obviously, the relatively large difference in projected operating costs between tilt-rotor and fixed-wing aircraft permits a reactive price strategy on the part of fixed-wing operators that could deflect successful tilt-rotor penetration. Without regulatory intervention or subsidy, the impact of fare premiums greater than $50 seems difficult to overcome.

If we use $50/hr for the value of travel time, the corresponding tilt-rotor shares of the commuter market when tilt rotors supplying airport-to-airport service compete with fixed-wing commuter aircraft increase from 25 percent to 44 percent, 27 percent to 47 percent, and 11 percent to 30 percent. As before, these fractions are approximately halved under the equal flight time assumption.

If we assume that the fare premium is roughly $30, the cities in Table 7 appear able to support at least minimal tilt-rotor commuter service, using a lower cutoff of two round-trips per day on average. A total of 42 daily round-trips (on average) could be successfully scheduled in 1995 if the fare premium can be maintained at $30, if tilt rotors achieve the flight time performance we have postulated, and if travel time is valued at $25/hr. This would be reduced to about 20 flights per day for the case of equal flight time performed. We designate the 42 round-trips per day as our baseline airport-to-airport forecast.

Is $25/hr a plausible estimate for the value of travel time? Our focus group and survey respondents were unwilling, when queried, to attribute even $25/hr to the value of their travel time. Despite this, we believe there could be a shift toward the higher figure (in constant 1987 dollars), but we think the shift would be more likely in the context of a Manhattan vertiport. Nevertheless, we have included the results of our market analysis for the case of the higher valuation of travel time, where nearly 50 percent of the commuter market could be captured by tilt rotors operating at a $30 fare premium. Table 4 shows only those cities with a forecast volume of 100,000 passengers per year. A number of smaller cities whose projected traffic

\[1\] This assumption of indifference is based on a change in passenger attitudes from those expressed by our focus group respondents, presumably as a result of improved technology, familiarity, and a successful marketing approach that erases the helicopter image.
Table 7

SCENARIO a: AIRPORT-TO-AIRPORT SYSTEM
(1996 Forecast)

<table>
<thead>
<tr>
<th>City</th>
<th>Average Round-Trips Per Day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At $25/hr</td>
</tr>
<tr>
<td>Providence</td>
<td>7.8</td>
</tr>
<tr>
<td>Philadelphia</td>
<td>7.2</td>
</tr>
<tr>
<td>Albany</td>
<td>7.7</td>
</tr>
<tr>
<td>Hartford</td>
<td>3.9</td>
</tr>
<tr>
<td>Worcester</td>
<td>1.6</td>
</tr>
<tr>
<td>Manchester</td>
<td>3.3</td>
</tr>
<tr>
<td>Harrisburg</td>
<td>2.6</td>
</tr>
<tr>
<td>Baltimore</td>
<td>4.8</td>
</tr>
<tr>
<td>Atlantic City</td>
<td>2.0</td>
</tr>
<tr>
<td>Nantucket</td>
<td>0</td>
</tr>
<tr>
<td>Binghampton</td>
<td>0</td>
</tr>
<tr>
<td>New Haven</td>
<td>0</td>
</tr>
<tr>
<td>Hyannis</td>
<td>0</td>
</tr>
<tr>
<td>Ithaca</td>
<td>0</td>
</tr>
<tr>
<td>Martha’s Vineyard</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>41</td>
</tr>
</tbody>
</table>

NOTE: 31-passenger capacity tilt rotor, 65 percent load factor.

Volume in 1995 was expected to be less than 100,000 passengers per year (at $50/hr) now appear capable of supporting limited tilt-rotor service. We have used a lower cutoff of an average of two round-trips per day, or about 29,000 passengers per year to and from New York, assuming a 31-passenger craft operating at a load factor of 65 percent. With a 47 percent share of the commuter market, a number of new small cities (shown in Table 7) exhibit potential for tilt-rotor operation: Nantucket, Ithaca, Martha’s Vineyard, and Binghampton. Service to these cities adds 12 more round-trips, and the total number of average daily round-trips is 80, compared to 42 for our baseline estimate.

In general, our forecasts suggest that the “small plane aversion” would prevent tilt-rotor operations between New York airports and Washington and Boston from achieving significant market share compared to jet shuttles. But the situation changes dramatically if tilt-rotor service to these markets can achieve the high levels of airside efficiency we assume and passengers become indifferent to intrinsic differences in size, amenities, and ride quality between tilt rotors and typical shuttle airplanes. If the small plane penalty is not assumed, we forecast a baseline of 50 and a high of 160 tilt-rotor round trips per day. This suggests that tilt-rotor manufacturers and operators would wish to pursue an aggressive marketing effort to promote public acceptance.
Scenario b

Scenario b refers to a vertiport site located in downtown Manhattan. We have made a preliminary forecast of 1995 aircraft movements and passenger volume for a generically located downtown/midtown vertiport. Later, after a number of candidate sites have been identified and detailed passenger preferences surveyed, a more precise forecast should be made. Scenario b reflects the preference that travelers exhibit for larger jet aircraft over turboprop commuter equipment. This preference does not influence consumer choice in markets served largely by commuter equipment (even up to 65-passenger aircraft) but plays an important role in demand forecasts for Washington, Boston, and other cities where competing service would be provided by larger jet aircraft. This preference has been included in our baseline prediction, plus we made a sensitivity analysis to understand the magnitude of the small plane penalty.

In addition to the aircraft size effect, the cost and time of ground service influence passenger choice, joining flight time and fare in determining the elements of a modal share model for estimating the relative demand for vertiport-based tilt-rotor service compared to the demand for fixed-wing service using existing Port Authority airports.

We used the 1984 Port Authority in-flight survey data to estimate that one-third of New York airline passengers originate in Manhattan, and that three-quarters of these passengers would travel to or from the region likely to be serviced by a downtown vertiport. The resulting 25 percent submarket is consistent with the fraction we estimated from our Albany survey.

We consider the region designated as Mid-East, Mid-West, and Lower Manhattan in the Hoyle-Tanner study as a submarket that would be serviced by a downtown vertiport. We have assumed that the average passenger using the vertiport would save 45 minutes in ground access time, 10 minutes in terminal transit time, and $14 in ground access costs, when compared to the use of a Port Authority airport. The submarket share is 25 percent of the entire market for commercial air transport in the Port Authority’s catchment area.

We recognize that some commuter passengers use Port Authority airports to connect with other flights, and would not be interested in a downtown destination. Data regarding this connecting fraction are limited, although individual airlines may possess proprietary data. Commuter travelers were not included to any extent in the 1984 passenger survey. We have relied on judgment, the OAG, and conversations with commuter operators to account for this group on a city-by-city basis. Philadelphia, for example, is a case where both the high connecting fraction and the availability of a frequent city-center-to-city-center rail service would diminish interest in a downtown vertiport. We have assumed, therefore, that few travelers between Philadelphia and New York would choose a vertiport. Commuter travelers to JFK are also assumed to be less likely to choose vertiport service.

Clearly, Washington and Boston would become the most important markets for vertiport users. From Table 8, we note that with the small plane penalty and a $25/hr value of time, a total of 25 average round-trips per day is forecast between these two cities and the downtown vertiport. For $50/hr, the predicted number of flights doubles to 48 round-trips. If tilt rotors increase in capacity, say, to 75 passengers, and if the traveler’s perception of the tilt rotor evolves closer to that of a 737 or larger jet, or if we have seriously overestimated the magnitude of small plane aversion, then even at $25/hr, the number of Washington and Boston passengers using the downtown vertiport could triple from 975 average daily passenger round-trips to 3150. However, a conservative baseline forecast must take the small plane penalty seriously, reinforced by the likelihood that a 31-passenger civil variant is far more likely to be available (during the next decade) than a 75-seater. Nevertheless, the possible tripling of passenger demand suggests that careful attention to passenger amenities and proper marketing
of technology that overcomes most of the small plane aversion could be extraordinarily worthwhile. It also suggests that supplementary service in Washington and Boston markets could be attractive to potential operators.

Our 1995 forecast suggests that an average of 52 round-trip flights per day could be supported by a vertiport located in the mid-town area of Manhattan. This corresponds to over 1000 round-trip passengers daily (2000/day), based on a 31-passenger vehicle operating at 65 percent capacity. The vertiport design should accommodate two types of growth. It should permit the use, ultimately, of larger capacity equipment, such as a 75-passenger craft, and it should accommodate increased passenger traffic. The possibility of increased traffic depends primarily on the degree of passenger acceptance. If passengers perceive that the time savings afforded by the close-in vertiport location could be used productively, a value of time closer to $50/hr may be more acceptable, and demand could easily double. Similarly, if passengers perceive the tilt rotor as superior to a fixed-wing airplane of similar or slightly larger size, then the small plane aversion penalty would not fully apply, and the baseline forecasts could be

<table>
<thead>
<tr>
<th>Cities with Significant Commuter Service</th>
<th>Average Round-Trips Per Day</th>
<th>At $25/hr</th>
<th>At $50/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albany</td>
<td>4.5 (2.5)</td>
<td>5.3 (2.5)</td>
<td></td>
</tr>
<tr>
<td>Baltimore</td>
<td>4.5 (3.0)</td>
<td>6.0 (4.0)</td>
<td></td>
</tr>
<tr>
<td>Philadelphia</td>
<td>0.0 (0.0)</td>
<td>0.0 (0.0)</td>
<td></td>
</tr>
<tr>
<td>Hartford</td>
<td>2.3 (1.3)</td>
<td>3.2 (2.0)</td>
<td></td>
</tr>
<tr>
<td>Providence</td>
<td>3.0 (1.0)</td>
<td>4.2 (2.2)</td>
<td></td>
</tr>
<tr>
<td>Harrisburg</td>
<td>1.5 (0.0)</td>
<td>2.1 (0.0)</td>
<td></td>
</tr>
<tr>
<td>Worcester</td>
<td>1.5 (0.0)</td>
<td>1.5 (0.0)</td>
<td></td>
</tr>
<tr>
<td>Manchester</td>
<td>1.5 (0.0)</td>
<td>3.0 (1.5)</td>
<td></td>
</tr>
<tr>
<td>Burlington</td>
<td>1.5 (0.0)</td>
<td>3.0 (1.5)</td>
<td></td>
</tr>
<tr>
<td>Atlantic City</td>
<td>1.5 (0.0)</td>
<td>2.0 (1.5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>21.80</td>
<td>7.8</td>
<td>30.30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cities with Limited/No Commuter Service</th>
<th>Average Round-Trips Per Day</th>
<th>At $25/hr</th>
<th>At $50/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washington</td>
<td>11.3 (3.4)</td>
<td>22.5 (10)</td>
<td></td>
</tr>
<tr>
<td>Boston</td>
<td>13.5 (6.0)</td>
<td>26.3 (12.5)</td>
<td></td>
</tr>
<tr>
<td>Montreal</td>
<td>1.5 (0.0)</td>
<td>2.3 (1.0)</td>
<td></td>
</tr>
<tr>
<td>Toronto</td>
<td>3.8 (1.2)</td>
<td>5.3 (2.5)</td>
<td></td>
</tr>
<tr>
<td>Norfolk</td>
<td>0.0 (0.0)</td>
<td>0.0 (0.0)</td>
<td></td>
</tr>
<tr>
<td>Syracuse</td>
<td>0.0 (0.0)</td>
<td>2.3 (1.0)</td>
<td></td>
</tr>
<tr>
<td>Rochester</td>
<td>0.0 (0.0)</td>
<td>1.8 (1.0)</td>
<td></td>
</tr>
<tr>
<td>Buffalo</td>
<td>0.0 (0.0)</td>
<td>0.0 (0.0)</td>
<td></td>
</tr>
<tr>
<td>Pittsburgh</td>
<td>0.0 (0.0)</td>
<td>3.5 (2.0)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30.10</td>
<td>64.0</td>
<td>(30)</td>
</tr>
<tr>
<td>Total</td>
<td>51.90</td>
<td>94.3</td>
<td>(45.2)</td>
</tr>
<tr>
<td>Passenger Total RT, Avg/Day</td>
<td>1,050</td>
<td>(372)</td>
<td>1,896</td>
</tr>
</tbody>
</table>

Note: 31-passenger tilt-rotor aircraft, 65 percent load factor, numbers in parentheses refer to equal scheduled block time assumption.
much too low. For a case of total passenger acceptance, where no perceived difference exists between tilt-rotor and jet service, the analysis predicts 49 round trips daily to Washington and Boston if time is valued at $25/hr and 109 round trips if time is valued at $50/hr.

We have assumed a tilt-rotor fare premium that permits average tilt-rotor operation to cover costs on each flight compared to a market-driven fixed-wing fare. These fare premiums, based on 1987 fare levels, are considerably greater for cities like Washington and Boston than for cities that are primarily served by commuters.

The importance of the flight time advantage is underscored by the substantial reduction in tilt-rotor share that occurs when tilt-rotor flight times equal those for fixed-wing service. For a time value of $25/hr, Washington/Boston tilt-rotor service drops to 10 round-trips a day and the total tilt-rotor market is reduced by two-thirds. For $50/hr, the tilt-rotor market is reduced by approximately 50 percent.

Scenario c

Scenario c involves vertiports that are dispersed, more or less optimally, throughout the New York/New Jersey area served by the Port Authority. The purpose of this forecast was to compare aggregate projections made using a simplified analytic methodology with those described in the Hoyle, Tanner Port Authority study. We have adapted the Hoyle-Tanner sub-market analysis to estimate that 76 percent of all passengers using Port Authority airports might consider using tilt-rotor service, given the proper mix of fare, time savings, and vertiport location. The remaining 24 percent are too close to Port Authority airports to be diverted to a local vertiport. We assume that a series of vertiports are located, on average, such that passengers save 45 minutes in surface access time, $14 in surface access costs, and 10 minutes in terminal transit time. Our 1995 forecasts are shown in Table 9, based on these parameters. We have estimated the savings in ground travel time that would follow from regional vertiports in the New York/New Jersey, Washington, and Boston areas, but have not proceeded with a complete (bottom-up) simulation of market dynamics because of the limited market share that tilt-rotor service achieves in even the most promising catchment area—that served by a Manhattan vertiport. No minimum vertiport traffic criteria are assumed and no siting analyses were performed. Many routes would not be financially viable, and limited schedules would severely dampen demand. Thus, scenario c provides an upper-bound aggregate estimate, and does not indicate the levels of service within each subregion. We judge that only the Manhattan mid-town vertiport would have a sufficiently large number of potential passengers to encourage aircraft and airport operators to proceed. The Hoyle, Tanner Port Authority report forecast a total of 4,302,000 annual O-D passengers to and from Washington, Boston, Baltimore, Philadelphia, Hartford, and Pittsburgh in 1995. Our baseline methodology forecasts 1,460,000 for these cities, with some possibility of reaching 2,850,000 passengers if travelers value time savings at $50/hr rather than $25/hr. These estimates are reduced by about 60 percent if tilt rotors are not able to provide marked flight time advantages over fixed-wing service. A much more detailed and elaborate study would be required to determine the precise optimal locations for vertiports throughout the Port Authority region.

We emphasize that our baseline forecasts for Scenarios a, b, and c depend on the ability of tilt-rotor technology and its supporting infrastructure to deliver time savings (both on the ground and in the air) in a manner perceived to be safe, reliable, and at least as comfortable as competing commuter aircraft operating in the New York area during the next decade. The data upon which our model parameters are based reflect an average mix of discounts,
restrictions, and promotional fares. As noted above, our sensitivity analyses suggest that cities such as Washington, Boston, Pittsburgh, and Toronto that are primarily served by jet equipment could offer potential for tilt-rotor market penetration if the small plane aversion can be mitigated.

What about pricing strategies? In the absence of subsidy or regulatory intervention, the system must operate at greater than break-even cost to be commercially attractive. If the tilt-rotor market share is small, then fixed-wing operators may not reduce their fares. Thus, the use of a cost-based tilt-rotor fare vs. a market-based fare for the fixed-wing service could then be plausible. However, fixed-wing operators might find ways to reduce fares to lower levels if their market share is seriously jeopardized, and in this way could compel tilt-rotor operators to either lower the tilt-rotor fares below cost or lose market share.

### Table 9

**SCENARIO c: OPTIMALLY DISPERSED VERTEXPORTS IN PORT AUTHORITY AREA**  
(1996 Forecast)

<table>
<thead>
<tr>
<th>City</th>
<th>Average Round-Trips Per Day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$25/hr</td>
</tr>
<tr>
<td>Washington</td>
<td>35.0</td>
</tr>
<tr>
<td>Boston</td>
<td>41.0</td>
</tr>
<tr>
<td>Baltimore</td>
<td>14.0</td>
</tr>
<tr>
<td>Philadelphia</td>
<td>0</td>
</tr>
<tr>
<td>Hartford</td>
<td>7.0</td>
</tr>
<tr>
<td>Pittsburg</td>
<td>0</td>
</tr>
<tr>
<td>Subtotal</td>
<td>97.0 (2000 passengers)</td>
</tr>
<tr>
<td>Albany</td>
<td>14.0</td>
</tr>
<tr>
<td>Providence</td>
<td>9.0</td>
</tr>
<tr>
<td>Harrisburg</td>
<td>4.6</td>
</tr>
<tr>
<td>Worcester</td>
<td>4.6</td>
</tr>
<tr>
<td>Manchester</td>
<td>4.6</td>
</tr>
<tr>
<td>Burlington</td>
<td>4.6</td>
</tr>
<tr>
<td>Atlantic City</td>
<td>4.6</td>
</tr>
<tr>
<td>Buffalo</td>
<td>0</td>
</tr>
<tr>
<td>Rochester</td>
<td>0</td>
</tr>
<tr>
<td>Syracuse</td>
<td>0</td>
</tr>
<tr>
<td>Norfolk</td>
<td>0</td>
</tr>
<tr>
<td>Toronto</td>
<td>11.5</td>
</tr>
<tr>
<td>Montreal</td>
<td>4.6</td>
</tr>
<tr>
<td>Subtotal</td>
<td>62.1 (1250 passengers)</td>
</tr>
<tr>
<td>Total</td>
<td>159.10 (3250 passengers)</td>
</tr>
<tr>
<td>Annual PAX</td>
<td>$2.33 \times 10^6$</td>
</tr>
</tbody>
</table>

**NOTE:** 31-passenger tilt-rotor aircraft, 65 percent load factor.
X. CONCLUSIONS

The preceding analysis employed a variety of analytical techniques to assess the potential of tilt-rotor aircraft technology in the New York metropolitan region. Focus groups, surveys, route analysis, and mathematical demand models were used to explore the potential of this technology for alleviating airport congestion in the New York region. The results were relatively constant. The unique features of the tilt rotor offer a significant opportunity to reduce airport congestion, but realizing such benefits may take many years. The estimated costs of the tilt rotor, public doubts about a vehicle that many associate with helicopters, and the unwillingness of the airlines to step forward imply that a minimally modified civil version of the V-22 will probably not gain significant market penetration. The problem of airport congestion is severe, but not yet severe enough to motivate the private sector to pursue this technology in the face of large market and technological uncertainties.

There is little doubt that tilt-rotor technology is promising, and that the infrastructure necessary to support a tilt-rotor system could be feasible (although La Guardia airport poses difficult problems). The crucial issues from the point of demand forecasts are tilt-rotor operating costs, the extent of consumer aversion to tilt rotors due to an association with helicopters, and the ability of a tilt-rotor system to provide efficient, safe, and reliable service at significant time savings. Another important question, not generally considered, is the question of who would operate the tilt-rotor aircraft. Would they be operated by certificated carriers, by commuter airlines, or by other entities not yet determined? Both the character of the operator and the nature of the total operating environment would determine the strategy to be adopted by both fixed wing and tilt-rotor operators. As we have noted, commuter operators are not now interested in providing service that diverts them from their main objective—to provide connecting service that enhances ticket revenues for their associated major carriers. A major restructuring of the air transportation industry would be necessary for them, or their major carrier partners and owners, to initiate city-center-to-city-center service. Furthermore, the estimated maintenance costs and reliability of tilt-rotor aircraft may be too close to that of rotary-wing equipment for operators of conventional fixed-wing equipment to consider them as suitable substitutes for less costly and more reliable modern turboprops.

We therefore conclude that an additional cycle of technology evolution bringing reduced costs, increased reliability, and increased public confidence will be required before airport operators can consider the vehicle as an option for reducing congestion. Internal and external noise, vibration, comfort, and amenity levels must be comparable with modern turboprop equipment for tilt rotors to compete successfully in the marketplace. Such improvements will be required to make investment in the vehicle appear to be an attractive business venture. At this time, the primary policy initiatives for stimulating these improvements do not lie with airport operators such as the Port Authority of New York and New Jersey, but with federal agencies (e.g., the FAA, NASA, and DoD), who must decide whether they can continue to promote this potentially attractive technology. They also lie with manufacturers who must decide whether a civil tilt rotor has sufficient market potential to warrant a major development effort.
THE TILT ROTOR AT THE THREE AIRPORTS

A central issue addressed in this study was the feasibility of operating the tilt rotor at the three existing airports in a manner essentially independent of fixed-wing aircraft. This would allow tilt rotors to replace small commuter aircraft, leaving the runways free for larger aircraft. Although such operation seems feasible given the proper supporting infrastructure, our findings suggest that subsidies or other nonmarket policies may be needed to stimulate the initiation of tilt-rotor service. Given the lack of a current mechanism for airport authorities to cross-subsidize different services, and the potential legal and political issues, we did not examine specific subsidy policies. However, the methods and results described in this report can be adapted to estimate the relationship between subsidy levels and reduction of fixed-wing commuter movements.

The Air Traffic Control Problem

Our analysis of the air traffic control problem indicates that the tilt rotor's unique flight profile presents the opportunity for independent operation. Through use of six-degree or greater descents and curved path approaches, tilt-rotor traffic can be separated from the choke points in the existing system. Implementation of this separation will require an appropriate precision navigation system such as MLS. The new flows will create new interactions with the fixed-wing traffic, which the controller should be able to cope with when the tilt-rotor traffic is not overly dense. As tilt-rotor traffic increases, we expect that the air traffic controller will ultimately employ automated decision support, surveillance, and communication systems to cope with the new interactions. Several FAA programs are likely to be implemented that would, as a collateral benefit, facilitate tilt-rotor operations. Suitable FAA standards for all aspects of tilt-rotor operations would also be essential.

Airport Infrastructure

Although airport space is a precious commodity, JFK and Newark are sufficiently large that there should ultimately be several options for landing tilt rotors. In both cases, the analysis identified procedures by which STOL runways might also be used, thereby reducing the costs of vertical operation. However, if these STOL areas become unavailable at JFK, there is no obvious location for a vertiport close to the terminal complex. The area may be redesigned and Port Authority officials should consider reserving space there now for tilt-rotor vertiport landings. Given the number of tilt-rotor passengers that will be connecting, we cannot recommend that a new terminal be built for the tilt rotor at this time. Instead the tilt rotor should be integrated into the existing gating and terminal system at JFK and Newark, which would still have additional fixed-wing capacity.

The center of the short-haul airport capacity problem in New York City is at La Guardia. This airport has no additional fixed-wing capacity, is the primary airport for nonconnecting commuter traffic to New York City, and as such is the most critical airport for this study. However, it is also the airport where it is most difficult to configure a tilt-rotor infrastructure. The employee parking area is a plausible landing area, but ground access to this location is difficult. If it is to be used for the tilt rotor, it appears that some form of people-mover or bus system would be the best means of bringing passengers to the terminals. Gate congestion and the clutter of aircraft on the ground make the movement of the tilt rotor to the gates an unlikely solution. More important, it must be recognized that any available land at La Guardia will be scrutinized for applications to other airport functions. It may be difficult to justify reserving the employee parking area for the tilt rotor in view of other probable demands.
Demand at the Airport

The major difficulty with basing tilt-rotor service at the Port Authority airports is that a market-driven service offers few direct benefits to passengers. It is possible that the tilt rotor will experience fewer air traffic delays than fixed-wing aircraft and therefore give the passenger some incentive for paying a higher fare. However, our analysis shows that the magnitude of time saving and expected cost differential is not likely to generate interest that would stimulate airlines to commit financial or even political support. Our baseline forecast of 42 round-trip commuter flights per day does not appear encouraging, and even the upper estimate of 80 movements seems less than promising.

Airlines have little incentive to promote the tilt rotor in place of fixed-wing aircraft. It is possible that in the future, when slots are at a premium, the airlines will have little alternative but to use the tilt rotor. However, the slot pricing picture presented in this report indicates that for the present, it will be more cost effective for airlines to bid for slots than to use the tilt rotor.

If tilt rotors could offer major advantages in actual block time, compared with jet shuttles between Washington or Boston and New York airports, and if passengers were indifferent to the intrinsic differences in size, amenities, and ride quality between tilt-rotor and jet transports, then these two markets could support a baseline of 50 round-trip flights daily. If the perceived dollar value of travel time savings is $50 per hour rather than $25, nearly 160 round trips are forecast. At present, however, we must view this as overly optimistic in the face of consistent evidence supporting the notion of “small plane aversion.” Therefore, only a major change in traveler attitudes, through education and marketing, would justify such forecasts.

The Prospects for Airport Operations

Although we believe that the tilt rotor could be used at the existing airports in a manner that is virtually independent of fixed-wing traffic, we have two important caveats. The situation at La Guardia is so constrained that it is difficult to state this conclusion with any confidence given the changes that are likely to occur in the upcoming years. Furthermore, the landing site we have identified is so difficult to access that any advantage the tilt rotor offers in terms of lessened ATC delays is likely to be erased by increased access time. Incorporating this factor in the analysis would make the demand forecasts even smaller than presented here.

It therefore seems clear that if the airport operators wish to promote tilt rotors as substitutes for commuter aircraft, financial incentives will be needed to induce airlines to choose the tilt rotor. Higher landing fees for fixed-wing aircraft might be used to finance tilt-rotor operation, or the Port Authority might purchase tilt rotors and lease them to operators at favorable rates. In the absence of such incentives, we cannot foresee airline or passenger interest in using the vehicle at major airports. Although airport operators would derive a considerable advantage from a large tilt-rotor market share, we expect that they will have a major marketing task to persuade passengers to use them.

A final observation is that proper criteria and standards must be established by the FAA, even on an interim basis for planning purposes. One problem to be considered is the simultaneous operation of a tilt-rotor vertiport and fixed-wing landing at a runway under instrument landing conditions. Optimal tilt-rotor landing locations at LGA and Newark place the tilt rotor in proximity with the runway (less than 2000 ft). A detailed set of measurements and safety tests must be conducted to verify the feasibility of independent operations under these conditions.
REGIONAL VERTIPORTS

A far more attractive system for passengers and ultimately for aircraft operators would be to fly tilt rotors from regional vertiports. Such a system might save passengers substantial ground travel time and could induce them to pay for the higher costs.

The Value of Travel Time Savings

Our focus groups and surveys identified the journey to the airport to be the major air travel problem. Nevertheless, passengers’ declared dollar value of time was not adequate to compensate for the additional estimated costs of the tilt rotor. The empirical literature, based on formal analysis of passenger behavior, not attitudes, was more ambiguous, suggesting a value range of between $25 and $50 dollars per hour. Our model analyses suggest that this range markedly influences the size of a tilt-rotor market based at a Manhattan vertiport. Many of our focus group participants indicated that timesaving was not particularly valuable since their trip required the entire day anyway. We therefore conclude that if the tilt rotor is perceived to be sufficiently reliable, travelers might begin to change their attitudes about a whole day trip and the difficulty of combining it with a few hours in the office. Should this occur, the higher dollar value of time may be the appropriate modeling assumption and the tilt rotor could capture a far more significant market.

A second problem involves the nature of vertiport markets and the competition. Since vertiports will capture mainly those passengers living or working nearby, the market is highly segmented. There will be limited demand for direct flights from a particular zone in New York City to a city like Buffalo and certainly not with the frequency offered at major airports. Even the Manhattan market captures less than might be expected, since many passengers depart for the airport from home rather than from the office. This observation underscores the need to create a new perception about the ability to combine a day’s business trip with a few hours in the office.

Given this segmentation and the importance of frequency, our analysis leads us to conclude that it is prudent at this time to consider service only between a Manhattan vertiport and Boston and Washington. Our baseline forecast was 30 round-trip flights per day for these cities, reaching 64 at the $50 per hour value for travel time saving. Albany, Providence, and Baltimore might support between 11 and 16 daily round-trip flights. Atlantic City is a special case in which we suspect that our analysis is overly pessimistic. The “high roller” market and the possibility of subsidy support the possibility of service to Atlantic City. Even for these markets, the tilt rotor would compete against popular shuttle services that offer high reliability, attractive scheduling, and large jets. Anxiety about the tilt rotor was expressed in the focus groups, and the literature demonstrates a passenger preference for large aircraft over small ones. We quantified these factors in our demand analysis, and the results demonstrated a significant dampening of the potential market for a downtown vertiport. However, should passengers ultimately gain the same confidence in the tilt rotor as they have in large jets, as well as a new appreciation of the value of saving ground travel time, then the demand for services from a Manhattan vertiport would be much greater than could be accommodated easily. In terms of passenger traffic, our most optimistic projection for Manhattan-Washington/Boston service reached 2150 passenger round trips daily if air travel time savings are significant, passengers value time at $50/hr, and travelers did not discriminate between tilt rotors and jet shuttles. Our most pessimistic projections for this service resulted in levels that are smaller by a factor of ten.

The need for business travelers to develop new attitudes about travel time savings, the need for a highly reliable vehicle to aid in this development, and the widespread anxiety about helicopters suggest that several years of tilt-rotor operating experience may be required before a
Manhattan vertiport will command a significant market. Nonetheless, the concept is attractive and there is certainly a market niche of executives and others who are comfortable with all types of aircraft and value their time at high rates. We therefore envision initiation of a high-end premium service from Manhattan to Boston or Washington as an initial step in building the type of public perception ultimately needed to justify a larger market. Although we have not found that the typical frequent flyer values his or her time sufficiently to motivate tilt-rotor use, there are clearly some exceptional travelers who do. The anticipated costs of the tilt rotor point to this subset of frequent travelers as the logical initial market. The Port Authority might consider promoting such a service, to operate from the Wall Street vertiport or a mid-town facility. Our forecasts also suggest that it is much too early to consider a series of regional vertiports beyond the one located in Manhattan, since our aggregate demand estimates for this system are perhaps one-third of earlier forecasts made by others.

A Related Problem

Passenger preference for a large vehicle points to the desirability of the further evolution of tilt-rotor technology. It also highlights the problem that with the V-22 capacity of 31 to 39 passengers, four or more tilt rotors will be required to carry the same number of passengers from New York City to Boston or Washington as can be accommodated by one jet in the shuttle service. The sky could be filled with tilt rotors. This analysis did not explicitly consider the problem of en route air traffic control, but it is clear that a successful Manhattan operation could dramatically increase the number of vehicles to be monitored. The tilt rotor has a different optimum cruising altitude than the shuttle, and it is possible that this will not create a major problem; however, more investigation is required before that conclusion can be definitively drawn.

POTENTIAL GOVERNMENTAL ACTIONS

Actions for the Port Authority

Our findings are less encouraging than we anticipated when we initiated the study. As a result, we believe the primary burden for stimulating further development of this potentially valuable technology should not fall upon the airport operator, and do not recommend any infrastructure development at the airports at this time. However, the tilt-rotor concept is nevertheless attractive. The Port Authority should adopt a prudent course of watchful waiting and encouragement, as there are few options for increasing capacity. In the event that tilt-rotor costs, reliability, and acceptance approach those of modern turboprops, the Port Authority should be prepared to:

- Reserve the employee parking area, or an area of comparable size, at La Guardia for tilt-rotor use as a prerequisite for further consideration of the tilt rotor at this airport and a similar though less critical consideration for Newark and JFK.
- Consider the possibility of subsidizing tilt-rotor operators at the existing airports. Such a subsidy would reflect the benefits to the airport system derived from tilt-rotor operations.
- Continue to evaluate siting of vertiports in Manhattan to determine the feasibility of building such facilities and to reserve use of land areas.
- Continue to study the siting of vertiports elsewhere in the region, but do not expend resources to reserve such areas or to fund detailed feasibility studies.
- Explore with potential operators the possibility of tilt-rotor supplementary service to fill a high-end premium market niche.
Actions for the Federal Government

Based on our analysis, it is clear that the tilt rotor offers a novel approach for increasing the capacity of the airport system—an approach that if further refined and perfected, could save billions of dollars of investments in other means for achieving airport capacity expansion. However, the financial and technical risks in developing this technology are high, and it is unlikely that a commercial version of the vehicle will be funded by the private sector without significant subsidy. The tilt rotor offers the potential of long-term benefits to the aviation system, but poses high risks to the aircraft developer. The federal government should therefore view the tilt rotor as a technique for improving airport capacity (much as it views improved air traffic control systems), rather than as a vehicle required to pass a pure market test.

Nonetheless, market factors are important, because a tilt rotor would expand airport capacity only if it appeals to travelers and operators. Although a reduction in vehicle capital and operating costs would be desirable, our analysis showed that the point-to-point travel advantages of the tilt rotor could offset significantly higher fares relative to the price of fixed-wing aircraft. Travelers will pay for reduced travel time if they perceive the tilt rotor to be as safe and reliable as larger fixed-wing aircraft.

The latter point is particularly critical in that maintenance-induced delays could erode the time advantages of the tilt rotor over fixed-wing competition. The high cost of maintenance may mean a higher frequency of unscheduled repairs. Mean time to failure for a truly competitive tilt rotor must be comparable with that of commercial jet or turboprop transports. Tilt-rotor developers must establish a frame of reference for the civil sector that is not helicopter-derived. The standard of comparison for manufacturers, travelers, and potential operators must be the fixed-wing service that will be operating after the turn of the century.

These requirements have implications for NASA, the FAA, and the DoD. Although our demand forecasts are not overly impressive, the FAA must recognize that the tilt rotor could become an alternative to other costly means for eventually enlarging capacity, and should view its costs in this context. Moreover, the FAA does not now possess the charter, resources, or inclination to sponsor a civil tilt-rotor development program, and the risks may be too high for aerospace manufacturers to press forward without the assurance of substantial government participation. The nature of such participation remains to be determined. Similarly, demonstrating that the tilt rotor is superior to the helicopter is not adequate to convince potential carriers of its role in their fleet. Tilt rotors must meet the safety, comfort, and reliability standards of jet transports and modern turboprops if they are to be taken seriously as an important factor in alleviating airport and airspace congestion. They must also operate in ways that are virtually independent of fixed-wing aircraft, particularly in congested terminal control airspace. It is not too early for the FAA, working with DoD, to explore both conceptually and in detail how this independence can be achieved. High priority should be given to formulating operating and air traffic control procedures, as well as functional requirements for communications, navigation, and surveillance systems that will optimally integrate tilt-rotor transports into the future National Airspace System.

Finally, the single most important factor in gaining market acceptance of the tilt rotor is completion of the V-22 program and successful operation of the vehicle by the military for several years. Only this program is likely to give the degree of confidence ultimately needed.

At this time, a rush toward an early commercial passenger version of the V-22 is probably not the optimal route to promoting the tilt rotor as a way to increase airport capacity. Although it is the quickest way to initiate commercial passenger service, such a vehicle may evoke little interest from potential acquirers, carriers, and passengers. The proper way to stimulate awareness of the tilt rotor's ability to capture large market shares lies in creating greater confidence in the vehicle rather than in achieving an early passenger version to replace shuttles or turboprops. A small vehicle for high-premium executive service, or use of a minimally changed V-22 variant for off-
shore oil services, precious cargo, and other applications may be the most effective way to prepare the market for this vehicle. As airport capacity worsens, the tilt rotor could gain increasing appeal. Until this occurs, time and resources should be spent on measures to improve the technology to better meet market needs. The premature introduction of a potentially promising concept could damage, rather than promote, the future of civil tilt rotors.
Appendix A

INTEGRATION OF THE TILT ROTOR INTO THE AIR TRAFFIC CONTROL SYSTEM

The New York Terminal Control Area (TCA) poses one of the most complex airspace problems in the air traffic system. Such areas consist of controlled airspace extending upward from the surface or higher to specified altitudes. Within this block of airspace, all aircraft are controlled by air traffic control (ATC) facilities and are subject to operating rules and pilot and equipment requirements specified in the Federal Air Regulations. Within the TCA airspace, control is provided by the Terminal Radar Approach Control (TRACON) except in the immediate vicinity of airports, where control is the responsibility of the airport control towers. Beyond the TCA, control is provided by the Air Route Traffic Control Centers (ARTCCs).

The positive control provided within the TCA assists in organizing the complex traffic flow and reducing the potential for midair collisions in the congested airspace. Even under visual meteorological conditions, reliance on “see and avoid” procedures is impractical in such an environment, and procedures based on instrument flight rules (IFR) are followed. The introduction of civil tilt-rotor (CTR) operations into this environment will be constrained by the ability to integrate those operations into the traffic flow and ATC procedures.

To provide additional airport capacity, CTR aircraft will need to have separate vertiports, whether located at existing airports or new sites, with independent arrival and departure routes from conventional traffic. Although it may be possible for CTR aircraft to use short runways (or parts of runways not being actively used by conventional traffic) at existing airports, the approach and departure speeds of CTR aircraft, particularly in the final approach, are likely to be such that mixing those aircraft with conventional traffic on the same runways will result in a decrease in capacity.

Some capacity may be gained at existing airports with CTR aircraft using fixed-wing (FW) approach and departure routes, but landing and taking off at vertipads clear of the runways, thereby allowing a FW departure or arrival to occur simultaneously. However, for significant capacity to be gained, the CTR operations will need to be independent of the FW operations.

Thus, appropriate approach and departure routes will need to be defined, linking entry and exit fixes in the terminal airspace with the vertiport landing pads. Beyond the entry and exit fixes, CTR aircraft will follow standard en route procedures. The arrival and departure routes between the entry and exit fixes and the vertiport will need to comply with the relevant criteria in the tilt-rotor terminal instrument procedures, yet to be established by the FAA. These criteria will define required clearances from obstacles and terrain, as well as limits on turn radius and descent rate. In addition, these routes must meet existing standards on separation from other arrival and departure routes.

The interface between the en route airway system and the terminal entry and exit fixes needs to be carefully designed. Each major airport has its own independent arrival waypoints and routes, which are generally aligned with the en route traffic flow so that systematic and consistent transitions from en route to terminal airspace can be maintained. In addition, low-altitude nonjet traffic has an entirely different traffic distribution pattern than does high-
altitude traffic (traffic above 18,000 ft). This mix of traffic is permitted to operate in the terminal transition areas in directions and routes that are cross grain to each other.

During en route flight, aircraft are separated by altitude as well as route, and the system can thus accommodate a wide range of speeds. As the traffic converges toward the terminal airspace, the ability to use altitude separation becomes more difficult, until eventually the aircraft are sequenced on arrival routes in trail, with controllers using speed adjustments to maintain separation. Apart from increases in separation necessitated by the speed differential between CTR aircraft and jet traffic, once a CTR aircraft is established in trail in the arrival stream, it will be difficult to sequence another aircraft into the slot created when it leaves the stream to follow a separate arrival route. Thus the air route system will need additional spurs and waypoints on the airways to allow CTR aircraft to leave and enter the en route airways without interfering with the flow of FW traffic. Such spurs and waypoints were a part of the ill-fated East Coast Plan, but they were not used to their fullest potential.

REQUIREMENTS FOR CTR TERMINAL PROCEDURES

To define appropriate CTR terminal procedures, three aspects need to be addressed:

- The navigation and guidance requirements to allow the CTR aircraft to follow the procedures;
- The air traffic control procedures and their impact on ATC workload;
- The separation standards necessary to ensure safe operations of both CTR and FW traffic.

Navigation and Guidance

For CTR arrival and departure routes to be flyable, consideration must be given to how the pilot will be able to follow the route in instrument conditions. Existing instrument procedures are largely based on the use of VOR (VHF Omnidirectional Range) and DME (Distance Measuring Equipment) beacons, combined with Instrument Landing Systems (ILS). This technology cannot easily meet the requirements for likely CTR routes, particularly in already congested airspace. Instead, what is needed is a system that can determine the position of the aircraft with respect to a predefined three-dimensional route through the airspace, including curved segments, and display both the aircraft position and the route to the pilot, in a way that aids the pilot following the route. Ideally, such a system would include both a situational display that would show the position of the aircraft and the route in terms of the structure of the airspace and location of prominent features, including the vertiport and ATC reporting points, and a flight director display that would indicate deviations left and right and above and below the desired flight path.

There are three potential navigational technologies that could meet these requirements: the Global Positioning System (GPS), Microwave Landing System (MLS), and inertial navigation systems (INS). GPS uses signals received from a constellation of earth-orbiting satellites to continuously determine the position of an equipped aircraft. This system is not yet fully operational, but will become so during the coming decade as additional satellites are launched. It generally requires no other equipment beyond the receiver on the aircraft (and of course the satellites), and can be used anywhere in the world. Position accuracy would be further improved by differential GPS.
An MLS transmitter generates an azimuth (directional) and glide-slope signal that allows an aircraft equipped with an MLS receiver to determine its position and altitude relative to the transmitter. Hence it can determine its position relative to any defined approach path and provide the pilot with guidance instructions to follow the desired path. Although curved and segmented flight paths are theoretically possible with MLS (one of its advantages over the existing ILS), such use has yet to be accepted. The FAA has expressed its intention of gradually replacing ILS with MLS; however, production difficulties with the MLS units have delayed the program, and very few units are currently operational. At least one, and possibly more, MLS transmitter would be required for every vertiport, depending on the range of approach and departure paths.

An INS uses accurate gyroscopes to determine the position of the aircraft by continuously measuring and integrating its acceleration in three orthogonal directions. It is functionally similar to GPS, although employing a different technology. Although it needs no external reference signal (unlike GPS), any errors in position gradually accumulate, since it can only be reset when the aircraft reaches a known position. However, modern INS equipment is so accurate that errors are usually only a few yards after a flight of several hours.

A wide range of other navigational techniques for determining aircraft position exists, including automatic integration of signals from two or more VOR/DME beacons (often termed Area Navigation, or RNAV), and Loran-C. However, these are generally not as accurate as the foregoing, and are less likely to be adopted for CTR navigation.

Accuracy and cost are important considerations in selecting a system. MLS has the highest accuracy, particularly close to the landing area where it is most important, but it has limited coverage. GPS provides reasonable accuracy at all locations, but it may not be accurate enough to conduct low-visibility final approaches. The accuracy of INS degrades during the flight, and is lowest during final approach, preventing its use as a low-visibility approach aid. It is therefore likely that a combined system will be used, perhaps MLS and GPS, or MLS and INS. If the INS position could be updated during the flight, such as by GPS, it might be accurate enough to use as a landing aid. An INS/GPS system might be possible, although both technologies are currently very expensive. Alternatively, since en route accuracy is less important, a combination of MLS with a lower-cost system, such as Loran-C, might be possible.

However its position is determined, a CTR aircraft would also need an on-board navigation computer that could store the route and other geographic information, and drive the displays showing the aircraft position relative to the route and other features. The route information could be manually entered by the pilot, but that could significantly increase workload at critical times, and would be liable to error. It is more likely that a large number of standard routes would be stored in the navigational computer, and the pilot would simply select them from a menu. Alternatively, with the advent of datalink communication between aircraft and air traffic control (discussed further below), it would be possible for the ATC computers to instruct the CTR navigational computer to select a route, or even to provide route coordinates in real time. With the development of CRT flight displays (“glass cockpits”) and flight management computers, the necessary technology for the CTR on-board equipment is already state of the art, although there may well be a number of implementation issues that will require considerable work.

Another guidance issue relates to conduct of IFR landings and take-offs. Currently, helicopters can be certified for instrument approaches only above certain minimum velocities.
The reason is that for low speeds (below 40 knots for the Sikorsky S-76), pilot workload required for "flight on the backside of the power curve" increases dramatically. However, this realm of flight is penetrated routinely under VFR conditions because of available visual cues. If these visual cues could be duplicated electronically, operations could be conducted in poor visibility at low approach speeds that previously were considered too hazardous.

Future electronic VFR (EVFR) technologies could provide the pilot with a visual presentation that would include visual cues that are needed to safely navigate at low forward speeds during IFR conditions. Potential EVFR technologies include:

- Low-light-level TV (LLTV);
- Forward-looking infrared (FLIR);
- Millimeter radar (MMR).

The possibility of slow speeds and higher angles of descent and climb out will radically alter the obstacle clearance requirements, potentially permitting CTR aircraft to operate into city center vertiports in most weather conditions, assuming that passengers will accept these unfamiliar maneuvers.

Air Traffic Control

Given a system of arrival and departure routes connecting the vertiports to entry and exit fixes, where the CTR aircraft merge with conventional traffic, and appropriate navigation aids and guidance systems on the aircraft, procedures must be established to control the flow of CTR aircraft in the terminal airspace. It can be assumed that in the en route airspace CTR aircraft will behave and be handled the same way as any other turboprop aircraft, although if significant volumes of CTR traffic arise, they may affect low-altitude sector workload, and in extreme cases require resectorization. In the terminal airspace and at the vertiports, special provision will need to be provided. New vertiports will require their own towers to control movement onto and off the landing pads, both on the vertiport surface and in the surrounding airspace. Vertiports at existing airports will generally require one, and possibly more, additional tower position to handle CTR operations, except at low traffic levels. If CTR aircraft use segments of inactive runways, or flight paths cross active runways, significant coordination workload will be generated.

Except under very light traffic conditions, it is unlikely that a single terminal controller can handle both conventional and CTR final arrival streams. Either further resectorization will be required, or some sectors will require multiple controllers, with separate controllers for conventional and CTR traffic. Further upstream, or in departure sectors, a single controller may be able to separate and merge the flows of conventional and CTR traffic. However, if CTR traffic increases the total volume of traffic in a sector, it will increase controller workload, and may result in the need for resectorization. Since many busy terminal areas are already reaching limits on sector size and controller workload, accommodating significant amounts of CTR aircraft may create serious difficulties.

Traffic flow management coordination between the TRACON and the ARTCC will also become more complicated, because CTR aircraft will be segregated from jet traffic by altitude in the en route airspace, then may have to be merged over portions of the terminal arrival and departure routes and use separate routes for final approach and climb out. Metering the flows of conventional traffic and CTR aircraft on multiple air routes feeding into a terminal airspace,
particularly one with several airports and vertiports, will significantly increase the complexity of an already difficult problem.

**Separation Standards**

Two aspects of separation standards affect CTR operations. The first is the separation that must be maintained between aircraft, and the second is the separation between arrival and departure routes required by the Terminal Instrument Procedures (TERPS) criteria.

Reduction in aircraft separation standards is currently being considered in order to increase airspace and runway capacity. The FAA has allowed reduction of in-trail separation on final approach to 2.5 n mi, under some circumstances, since 1986. Additional spacing adjustments will depend on further wake and turbulence considerations. A reduction in diagonal separation requirements from 2 n mi to 1 n mi for dependent parallel operations under IFR conditions would increase capacity by 25 percent, according to studies by the MITRE Corporation (Lebron, 1987). Separation standards and capacity are complex topics that will affect all aircraft, not only CTRs. The CTR as well as the entire airline industry would benefit from improvements in this area.

Runway acceptance rates can also be increased by the use of converging or multiple approaches, as well as by permitting independent approaches to parallel runways closer than the present standard of 4000 feet. Such considerations would affect CTR operations to and from separate vertiports at existing airports, depending on the extent of CTR and FW traffic interaction.

One factor that is particularly relevant to CTR operations is the difference in capacity associated with the centerline distance between runways. If the vertipad can be located at least 2500 feet from the centerline of any adjacent runway, then the separation standards for dependent parallel runways can be applied, increasing capacity by approximately 25 percent for multiple dependent approaches. A separate, independent arrival or departure route from the vertipad could result in a 33 to 100 percent capacity increase, depending upon the baseline established. If the CTR system operated independently of the FW arrival and departure flows, capacity increases would depend upon the number of aircraft operating and not the delays that arise when operating in current arrival and departure traffic flows.

Revising the TERPS criteria is essential if the CTR is to be used effectively. Two important factors are the reduction in the turning radius that a CTR can achieve and the ability to safely navigate glide slopes in excess of 6 degrees. The FAA is reviewing TERPS for FW operations. It is hoped that the revised FW TERPS will adequately cover the CTR, including both steep glide paths and flight path separation standards.

Separation standards within the TCA are driven by the ability of ATCs to accurately monitor the position of all aircraft in the area. Monitoring could benefit from a more precise radar. Current radars present updates approximately once every 5 seconds. Precision radars that update approximately once per second would be needed to properly reduce separation standards. The fast scan monopulse radar could help achieve the desired surveillance accuracy. The use of this new radar may allow simultaneous approaches to runways as close as 3000 feet between centerlines.

Reduced separation standards raise the question of maintenance of acceptable levels of safety. This has been traditionally viewed in terms of air traffic control procedures; the development of the Traffic Alert and Collision Avoidance System (TCAS) will provide pilots with an independent aid for maintaining safe separation from surrounding traffic.
The FAA has established requirements that TCAS equipment be aboard all aircraft with 10 or more passenger seats by the mid-1990s. TCAS I, which is intended for small aircraft, will provide traffic advisories only. TCAS II will be required for larger commercial aircraft; it will also recommend climb or descent resolution advisories. It will have improved bearing accuracy and will respond appropriately when an "intruder" changes altitude. TCAS III will add horizontal resolution advisories to resolve conflicts.

Since TCAS is based on aircraft transponder signals, the future addition of Mode S transponder data link capability will enable two TCAS III aircraft operating in the same area to coordinate resolutions with each other, as well as with the ATC system on the ground. Beyond TCAS, more advanced systems for Cockpit Display of Traffic Information (CDTI) will allow a pilot to monitor air traffic in his vicinity while simultaneously providing information to ATC, thus providing controllers with data to manage situations, develop strategies, and anticipate traffic problems. Allowing the pilot to solve immediate problems provides additional safety margins and a degree of robustness when the system becomes saturated with aircraft, although specialized training may be required to properly utilize the system. Such cockpit advances may not be suitable for the average pilot in the National Airspace System, but neither are CAT II approaches. However, pilots of technologically advanced aircraft can routinely perform these operations, safely and consistently, provided the system responds to their needs. The future system cannot be developed around the weakest link, as it has in the past.

CONTRIBUTION OF IMPROVED ATC TECHNOLOGY

Fortunately, the problems of accommodating CTR aircraft in the air traffic control system will be eased by several programs now being implemented or planned as part of the modernization of the national ATC system being undertaken by the Federal Aviation Administration under its Capital Investment Program (formerly the National Airspace System Plan). These include significantly increased levels of automation, as well as improved surveillance and communication systems.

The current ATC system relies heavily on human judgment of future aircraft position. The ability of controllers to do this is constrained by the volume of traffic that they must handle and by their other tasks. Under conditions of heavy workload, they compensate by simplifying the traffic flow, at the price of loss of capacity or increased fuel consumption. Increased automation and computer assistance are expected to result in better management of the airspace and reduction of controller workload. Present ATC requirements must be updated to reflect future technology.

Traffic Flow Management

Responsibility for the coordination of both FW and CTR traffic moving into and out of a TCA will be divided between Central Flow Control (CFC) and the ARTCC. CFC provides strategic control, by establishing controlled departure times (CDTs) and assigning flight routes. The ARTCC provides more tactical control, assigning flight levels and speeds to sequence aircraft entering the TCA. Both these functions will benefit from improved future systems.

The Advanced Traffic Management System (Medeiros, 1989) will provide advanced display and planning tools, both to assist CFC personnel in developing strategic plans and to coordinate with the traffic management unit personnel at each ARTCC. The Aircraft Situation Display (ASD) currently provides controllers with visual information on the traffic
situation at varying levels of detail, as well as estimated arrival times at downstream waypoints. Future functions will add automated tools to ASD capabilities. Monitor/Alert will project traffic demands on airports, sectors, and fixes, and generate alerts when demand is projected to exceed preset thresholds. Automated Demand Resolution will generate alternative flow control plans for situations where demand exceeds capacity. In later phases of development, expert systems will evaluate alternative plans and implement a strategic decision function, as well as provide automated distribution of traffic management messages.

Key to the improvement of ARTCC tactical capabilities is the Advanced Automation System (AAS). Together with the workstation capabilities provided by the Initial Sector Suite System (ISSS), the AAS provides the framework upon which future automated ATC functions will be based. The AAS architecture consists of hardware and software subsystems to manage flight plan data and radar and other sensor inputs, perform tactical and strategic planning functions, and handle display data management and controller interface processing, as well as system monitoring and control functions (Benel et al., 1989). Building on the AAS will be the software capabilities of the Automated En Route ATC (AERA) program (Gish and Zimmerman, 1986). Planned to be deployed in three phases, this program will provide enhanced capabilities to detect and resolve conflicts between planned aircraft trajectories and other aircraft, flow control restrictions, and special-use airspace or terrain.

The combined capabilities of these traffic flow management systems will enhance the ability to coordinate departure times between FW and CTR traffic and sequence traffic inbound to terminal areas, so that CTR and FW traffic flows can be merged and separated as necessary, without excessive controller workload or loss of potential runway or airspace capacity.

Terminal Air Traffic Control Automation

The development of ATC automation aids for terminal airspace is not as advanced as for en route airspace. Until recently, it had been the FAA's intention to eventually consolidate existing TRACONs with the ARTCCs in combined facilities, referred to as Area Control Facilities (ACFs). These would of course be equipped with the AAS and the new sector suites, which would provide the platform for terminal control automation. This plan is now on hold, the TRACON computers are being upgraded, and there is some uncertainty about the long-term future for terminal control.

Meanwhile the FAA is proceeding with a research and development program for Terminal ATC Automation (TATCA). It will provide similar planning tools as AERA, but be designed for the special needs of the terminal environment (Boswell et al., 1990). Particular emphasis will be placed on sequencing arriving traffic and identifying minimum fuel burn descent profiles. The Center Tracon Automation System (CTAS), being developed at NASA Ames Research Center, consists of an integrated set of trajectory and sequencing algorithms and expert systems to help controllers assign route and descent profiles to inbound aircraft to achieve optimum spacing and sequence at the runway threshold with minimum fuel burn (Perry and Adam, 1991).

Airport Surface Traffic Control Automation

Airfield surface traffic has traditionally been controlled primarily by visual surveillance, supplemented in some cases by Airfield Surface Detection Equipment (ASDE) radar; however, a research and development program is also under way to provide automated surveillance and planning aids for tower controllers (Lyon et al., 1990). A three-phase development will provide
automated alerts, planning tools, and digital communication with aircraft. Although this program is motivated largely by the need to increase the safety of airfield movement under poor visibility conditions and to reduce taxiing delays, it will assist in coordinating the movements of CTR and FW aircraft on the airfield, particularly where CTR arrival and departure routes cross active runways.

**Mode S Data Link**

An important technology for reducing controller workload is the use of digital data links between the ATC computers and the aircraft flight management and cockpit display systems. By permitting transmission of routine information or revised clearances without using voice radio channels, not only will the controller be relieved of time-consuming tasks, but the possibility of error or misunderstanding will be reduced. The introduction of Mode Select (Mode S) radar, with its ability to exchange digital messages with individual aircraft transponders, will provide one platform for such data link messages.

**SUMMARY**

Current developments in ATC technology and aircraft navigation and guidance, combined with ongoing efforts to review aircraft separation standards and criteria for terminal instrument procedures, suggest that it should be technically possible for future CTR operations to be conducted under IFR largely independently of FW traffic in the terminal airspace. However, considerable work still needs to be done to define appropriate planning criteria for locating vertipads at existing airports, identifying feasible arrival and departure routes, and developing requirements for navigation aids. If ongoing airport and airspace planning is to address the potential requirements for future CTR facilities, these issues must be resolved fairly quickly, before options are precluded or constrained by near-term development.

**REFERENCES TO APP. A**


Appendix B

REVIEW OF PREVIOUS MODELS

MODEL CALIBRATIONS

In order to select appropriate parameter values, a number of previously published mode and route choice model calibrations were examined. Two addressed intercity mode choice (Grayson, 1981; Morrison and Winston, 1985), two addressed airline route choice (Kanafani and Ghobrial, 1985; Hansen, 1988), two addressed airport choice (Kanafani et al., 1975; Harvey, 1987), and one addressed airport ground access mode choice (Gosling, 1984). The calibrated parameter values for cost, travel time, and schedule delay for each of the models are shown in Table B.1, converted to a consistent system of units. The models did not measure schedule delay the same way. Four of the models used flight frequency rather than schedule delay—two directly, one as the logarithm of the frequency, and one as a more complex parabolic function, as noted on Table B.1.

When comparing parameter values for different model formulations, it is important to take account not only of differences in the units for the variables, particularly the constant dollar value of cost data, but also the effect of the structure of the utility function. Figure B.1 shows the effect on the utility function of different schedule delay formulations, for varying

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Grayson</td>
<td>-0.0328</td>
<td>-0.018</td>
<td>-0.200×Y</td>
<td>-0.0244×Y</td>
</tr>
<tr>
<td>Morrison and Winston</td>
<td>-0.00371</td>
<td>1977</td>
<td>-0.0020</td>
<td>-0.051</td>
</tr>
<tr>
<td>Kanafani et al.</td>
<td>-0.04</td>
<td>1970</td>
<td>-0.014</td>
<td>-0.10</td>
</tr>
<tr>
<td>Kanafani and Ghobrial</td>
<td>-0.0278</td>
<td>1980</td>
<td>-0.0201</td>
<td>-0.897</td>
</tr>
<tr>
<td>Hansen</td>
<td>-0.0045</td>
<td>1985</td>
<td>-0.0043</td>
<td>-1.45</td>
</tr>
<tr>
<td>Harvey</td>
<td>n/a</td>
<td>1980</td>
<td>-9.96</td>
<td>(0.94-0.055×F)F</td>
</tr>
<tr>
<td>Gosling</td>
<td>-1.74/PCI</td>
<td>1980</td>
<td>same</td>
<td>-1.10</td>
</tr>
</tbody>
</table>

NOTES:
1. Y = Household income/2000 ("wage rate")
   PCI = Household income per capita/1000 (children counted as 0.5 adults) = 0.7×Y (approx.)
   F = Daily departures
2. Morrison and Winston included party size variable (auto mode only) = 1.365×N
3. Morrison and Winston based schedule delay on average time in minutes between departures over 24-hour day. Parameter adjustment for schedule delay in hours for a 15-hour day:
   \[ P_2 = 15×7/(2×D) = P_2×10080/d, \text{ where } D = \text{weekly departures} \]
   \[ P_2 = -0.276 \]
4. Schedule delay parameter for Harvey model based on (15 + F) daily departures in market and series expansion of relative frequency ratio
5. Gosling and Harvey model parameters for Bay Area residents.
flight frequency, normalized to give the same values at five and ten flights per day. Although the different formulations give similar values over the mid-range of frequency, the differences increase sharply at low and high frequencies. It can be seen that the linear frequency term deviates the most from the traditional schedule delay formulation.

Grayson (1981) estimated a logit model of intercity mode choice based on the 1977 National Travel Survey. Auto and air modes were included in the model. Auto costs were based on $0.05 per mile plus $25 per 350 miles to allow for lodging. Air costs were based on coach fare. Costs were computed on the basis of travel party size, with travel times counted once. Auto travel times were based on a speed of 50 mph. Air travel times were based on the fastest scheduled flight time, with no allowance for airport access/egress.

Morrison and Winston (1985) developed logit models of intercity mode choice for both vacation and business travelers, using the same data source as Grayson, with supplementary data from various travel guides. The business travel model comprised auto and air modes. Auto costs were estimated at $0.152 per mile, based on the median reimbursement rate for business trips. Air fares were based on the median available discount fare in the market. Lodging and food costs were also included, based on the trip duration. Costs were computed for the travel party, with travel times counted once. Auto travel times were based on a speed of 40 mph and a maximum distance of 400 miles per day. Air travel times were based on scheduled flight times plus five hours for airport access and egress. A more recent paper by Morrison and Winston (1989) used a logit model to explore the effects of deregulation.
Kanafani et al. (1974) calibrated a simple logit model of air passenger route choice in the California corridor between the Bay Area and Los Angeles region, in which the choice of airports at either end of the trip was determined by air fare and service frequency differences between different airport pairs and total travel times, including airport access and egress times at each end of the trip. A later study by Kanafani and Ghabrial (1985) used data on air passenger itineraries from the national 10 percent ticket sample to develop a model of air passenger route choice, on the basis of fare, frequency, and travel time differences. The model included dummy variables for aircraft size and nature of en route stops (same flight or connecting).

Hansen (1988) extended the work of Kanafani and Ghabrial to study competitive aspects of airline hub operation. He calibrated a logit choice model using data on passenger itineraries from the 10 percent ticket sample, including the actual fare paid. The model expressed the schedule delay in terms of the logarithm of the frequency, and accounted for different flight frequencies on the segments into and out of a hub. Travel time was not explicitly included in the model, but was accounted for by a distance term. The model included a dummy variable for direct service, but did not account for differences in aircraft size.

Harvey (1987) developed a logit model of airport choice in the San Francisco Bay Area, using data from the 1985 Air Passenger Survey conducted by the Metropolitan Transportation Commission. The model included terms accounting for the frequency of service at the three airports and the highway travel times to reach each airport. Fare differences were not considered, since no data were available on the fares paid by each party. Two terms were used to measure the effect of flight frequency. One was simply the airport's share of the direct, non-commuter flights to the destination from all three airports. The other was a parabolic function of the total direct flights to the destination from the airport, which could assume a maximum value of nine flights per day.

Gosling (1984b) calibrated an airport access mode choice model for trips to San Francisco Airport from the North Bay, using data from the 1980 MTC Air Passenger Survey. The model included private auto (drop-off and park), rental car, and airport bus. There was negligible taxi or transit use in the market. The schedule delay term for the airport bus services was based on the actual flight time and bus schedules, assuming passengers took the latest bus that reached the airport at least 20 minutes before flight departure. Since highway travel times by all modes were essentially the same, the schedule delay provided the only significant time difference, and thus a significant value for a separate parameter for travel time was not obtained. The cost parameter was expressed as a multiple of the per capita household income in thousands of dollars, with children counted as 0.5 adults. Separate parameters were calibrated for resident and nonresident trips.

The different models were used to compute the effect of varying travel cost and travel time on the proportion of passengers choosing each mode in a two-mode situation, with costs adjusted to consistent units, as shown in Figs. B.2 and B.3. It can be seen that direct application of the models gives a wide range of results, and closer examination of the models is necessary.

**INTERPRETATION OF THE PARAMETER VALUES**

Because of the different structure of each model, direct comparison of parameter values can be misleading. However, the implied value of travel time can be compared for those models that included both cost and travel time variables, as shown in Table B.2. The schedule
Fig. B.2—Market share vs. cost difference

Fig. B.3—Market share vs. time difference
Table B.2
COMPARATIVE IMPLIED VALUES

<table>
<thead>
<tr>
<th>Model</th>
<th>Value of Travel Time (1987 $/hr)</th>
<th>Schedule Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Adjusted Parameter</td>
</tr>
<tr>
<td>Grayson</td>
<td>0.61* Y</td>
<td>1.22</td>
</tr>
<tr>
<td>Morrison and Winston</td>
<td>25.50</td>
<td>5.40</td>
</tr>
<tr>
<td>Kanafani et al.</td>
<td>7.14</td>
<td>-0.14*</td>
</tr>
<tr>
<td>Kanafani and Ghobrial</td>
<td>44.6</td>
<td>-1.59*</td>
</tr>
<tr>
<td>Hansen</td>
<td>337</td>
<td>-1.19b</td>
</tr>
<tr>
<td>Harvey</td>
<td>n/a</td>
<td>-1.00c</td>
</tr>
<tr>
<td>Gosling</td>
<td>0.83* PCI</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*Schedule delay $S = 7.5/F, S(F = 5) - 1.5; S(F = 10) - 0.75 \Rightarrow S = 2.25 \cdot 0.15* F (approx.).

**U(S - 0.75) = 2.97; U(S = 1.5) = 2.08 \Rightarrow U = 3.86 - 1.19* S.

\*U(S = 0.83) = 4.00; U(S = 1.5) = 3.33 \Rightarrow U = 4.83 - 1.00* S.

delay premium (ratio of scheduled delay parameter to travel time parameter) can also be compared for each model, by estimating an equivalent schedule delay parameter for those models that include a flight frequency term.

The implied values of travel time show a wide range from around $7.00 per hour to over $300 per hour (1987 dollars). Hansen (1988) notes that the high implied value of time in his model is due to an implausibly low fare parameter, which may in part reflect restrictions on the use of discount fares by business travelers. Both Grayson (1981) and Gosling (1984b) have terms that include income variables, with quite similar values. Assuming an average air passenger 1987 household income of $80,000 and an average household size of 2.5 implies a value of time between about $19 per hour (Gosling) and $24 per hour (Grayson). These values are somewhat lower than the value found (and used) by Morrison and Winston (1989) and much lower than the value obtained by Kanafani and Ghobrial. However, Kanafani and Ghobrial assumed that passengers based the choice on the one-way economy fare. The presence of discounted fares in practice would result in the calibration underestimating the fare parameter value, giving an overestimate of the implied value of time. An average fare discount of 40 percent is not implausible, even in 1980, giving an adjusted value of time of $27 per hour. It should also be noted that the lower value obtained by Gosling may reflect the relatively smaller time differences that arise in ground access systems, compared to flight schedules.

The schedule delay premium shows less variation across the models, varying between 1.0 and 1.8, if the results from Morrison and Winston and Harvey are ignored.

On the basis of the above comparison, it was decided to adopt the following parameter values, by setting the travel time parameter as shown, then selecting an implied value of time of either $25 or $50 per hour, and a schedule delay premium of 1.2:

\[ a_0 = -1.5, a_1 = -0.04 \text{ or } -0.02, a_2 = -1.2, a_3 = -1.0, \text{ and } a_4 = -1.17 \]
QUALITY OF SERVICE ISSUES

Since the mode-specific constant \( a_0 \) is equivalent to a time penalty of 1.5 hours of additional flight time, it clearly will have a significant effect on the outcome of the analysis. Indeed, a central question in any analysis of potential tilt-rotor markets is how travelers would choose between tilt-rotor service and conventional air service, all other things (fares, flight time, frequency, etc.) being equal. In terms of passenger acceptance, the tilt rotor is likely to lie somewhere between a large turboprop aircraft and a helicopter. Ride quality en route is likely to be as good as (and perhaps better than) a turboprop, while vertical take-off and landing will have obvious association with helicopters. The cabin size and seating arrangements, at least for the first craft likely to become available, will be similar to a small or medium-sized turboprop. With careful marketing, the tilt rotor may acquire a certain glamor that could offset size and ride quality disadvantages. On the other hand, the public perception of the safety of tilt-rotor operations is largely unknown, and may be quite cautious until substantial operating experience is accumulated. Needless to say, any accidents in the early years of tilt-rotor operation would seriously hurt traveler perceptions. Our focus group respondents seemed generally negative in their attitudes toward helicopters, and were concerned about tilt rotors using landing pads located on roof tops. This suggests that the tilt rotor should be presented as a turboprop that can also take off and land in a small area, rather than as a helicopter with improved forward flight abilities. Furthermore, a trusted and familiar name associated with fixed-wing aircraft also seems desirable to enhance positive traveler attitudes. This refers both to the manufacturer and the operator of the equipment.

It is likely that passenger perception will also be influenced by the type of airline operating the tilt-rotor services. Large, established certificated carriers would not only suggest a high standard of maintenance and pilot training, but would also have the resources to provide the same level of ticketing and terminal services that passengers are used to experiencing with conventional air service. Smaller or more specialized operators may be viewed more as commuter airlines. On balance, it appears that treating the tilt-rotor aircraft as similar to an equivalent-sized turboprop operated by a commuter airline represents a generally favorable but plausible assumption in terms of passenger perception.

The dummy variable parameter value for aircraft with fewer than 30 seats estimated by Kanafani and Ghobrial provides one approach to allow for the effect on passenger choice of the difference between commuter and jet aircraft. MacNeal (1981) discusses two other approaches, based on quality of service indices.

The Civil Aeronautics Board Quality of Service Index (QSI) was widely used in Board rate-setting cases. It was based on an econometric study of the factors affecting choice of flight in several hundred markets over two nine-month periods in the late 1960s. The QSI for a particular flight is calculated as follows:

\[
QSI = F \times E \times S
\]

where
- \( F \) = Number of days per week that the flight operates
- \( E \) = Equipment factor
- \( S \) = En route stop factor:
  - Nonstop = 1.00
  - One-stop = 0.55
  - Two-stop = 0.40
  - Three or more = 0.03
The equipment factor attempts to capture the effect of aircraft size and type. Text table (i) gives factors estimated in the study.

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet</td>
<td>1.30</td>
<td>DC-8-61</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>B-727, B-737, DC-9-30</td>
</tr>
<tr>
<td></td>
<td>0.78</td>
<td>BAC-1-11, DC-9-10</td>
</tr>
<tr>
<td>Turboprop</td>
<td>0.75</td>
<td>Electra</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>CV-580</td>
</tr>
<tr>
<td></td>
<td>0.43</td>
<td>F-27, FH-227</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>N-262</td>
</tr>
</tbody>
</table>

The aircraft types considered were limited by the date of the study. The strong correlation between aircraft size and equipment factor also raises questions of cause and effect. Did more people fly the carrier with the larger equipment because it was inherently more attractive, or did the carriers operating the larger equipment do so because they were able to attract more traffic (perhaps for reasons quite unrelated to the equipment operated)? The differences in the equipment factors for jet aircraft suggest the latter. It is hard to imagine that people care much whether they are on a DC-9-10 or a DC-9-30. Indeed, if anything, the larger aircraft might be expected to be less attractive, other things being equal (more crowding, etc.). Figure B.4 shows the equipment factors plotted against aircraft size, expressed as number of seats.

Figure B.4 suggests that for a given aircraft size, turboprop aircraft have an equipment factor only about 0.1 lower than jet aircraft. On the other hand, if the equipment factor really captures a disutility associated with smaller aircraft (and not simply a correlation between traffic volume and aircraft size), then this suggests that a 30-seat turboprop would have a QSI of only about 20 percent of a typical jet aircraft (e.g., a B-737), other things being equal. Unfortunately, we are not aware of any empirical studies linking QSI to market share. Based on the derivation of QSI, one would expect market share to be roughly proportional to QSI, absent any fare difference. This turns out to be consistent with the results described below, using a different approach.

The second approach, also developed by MacNeal, uses a scoring technique to compare different services. Points are assessed based on the number of flights in different periods of the day and such other factors as en route stops, propeller equipment, and whether operated by a commuter airline. The scoring rules are complex. The resulting score ("Service Class") is then used to study the effect of changes in service on traffic (e.g., using a particular route). No consideration is given to any differences in fare (the method was developed during CAB regulation, when there was little or no fare competition). On the basis of the results of various studies, MacNeal suggests that an improvement in service of one class in a market stimulates a growth in traffic of about 15 percent, whereas an improvement of one class relative to a competing service increases the share of the improved service by between about 10 and 20 percent.

Using MacNeal's rules, a change from commuter turboprop service to air carrier jet service in a market would improve the service class by about 3, other things being equal. Thus, if a market were served by two commuter carriers, each providing equivalent service (and each having 50 percent of the market), and one were replaced by jet service at the same frequency, the commuter share would drop to between about 15 and 25 percent. A commuter share of 20 percent would, other things being equal, require a logit model mode-specific constant for the
Fig. B.4—Effect of aircraft size on QSI

commuter service relative to jet service of -1.4. The similarity between this value and that estimated by Kanafani and Ghobrial is quite encouraging.

Table B.3 lists fixed-wing fares, flight times, and estimated delays, along with estimated tilt-rotor block times and fares.
<table>
<thead>
<tr>
<th>Code</th>
<th>City</th>
<th>Fixed Wing</th>
<th>Tilt Rotor</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Air Distance (n mi)</td>
<td>Fare Rate ($/n mi)</td>
<td>Air Fare ($)</td>
<td>Flight Time (Hr)</td>
<td>Delay (Hr)</td>
<td>Block Time (Hr)</td>
<td>Fare ($)</td>
</tr>
<tr>
<td>BOS</td>
<td>Boston</td>
<td>160</td>
<td>.39</td>
<td>62</td>
<td>1.00</td>
<td>.50</td>
<td>.78</td>
<td>114</td>
</tr>
<tr>
<td>BWI</td>
<td>Baltimore</td>
<td>159</td>
<td>.53</td>
<td>85</td>
<td>1.02</td>
<td>.25</td>
<td>.78</td>
<td>113</td>
</tr>
<tr>
<td>DCA</td>
<td>National</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IAD</td>
<td>Dulles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WAS</td>
<td>Washington</td>
<td>185</td>
<td>.37</td>
<td>68</td>
<td>1.25</td>
<td>.50</td>
<td>.97</td>
<td>124</td>
</tr>
<tr>
<td>PHL</td>
<td>Philadelphia</td>
<td>81</td>
<td>.62</td>
<td>50</td>
<td>.72</td>
<td>.25</td>
<td>.52</td>
<td>80</td>
</tr>
<tr>
<td>PIT</td>
<td>Pittsburgh</td>
<td>264</td>
<td>.36</td>
<td>79</td>
<td>1.25</td>
<td>.25</td>
<td>1.13</td>
<td>157</td>
</tr>
<tr>
<td>ALB</td>
<td>Albany</td>
<td>127</td>
<td>.58</td>
<td>74</td>
<td>1.00</td>
<td>.25</td>
<td>.67</td>
<td>100</td>
</tr>
<tr>
<td>BUF</td>
<td>Buffalo</td>
<td>253</td>
<td>.27</td>
<td>68</td>
<td>1.18</td>
<td>.25</td>
<td>1.09</td>
<td>153</td>
</tr>
<tr>
<td>ROC</td>
<td>Rochester</td>
<td>221</td>
<td>.29</td>
<td>65</td>
<td>1.13</td>
<td>.25</td>
<td>.99</td>
<td>139</td>
</tr>
<tr>
<td>SYR</td>
<td>Syracuse</td>
<td>176</td>
<td>.39</td>
<td>69</td>
<td>1.06</td>
<td>.25</td>
<td>.84</td>
<td>120</td>
</tr>
<tr>
<td>ABE</td>
<td>Allentown</td>
<td>66</td>
<td>.53</td>
<td>35</td>
<td>.67</td>
<td>.25</td>
<td>.47</td>
<td>74</td>
</tr>
<tr>
<td>ACK</td>
<td>Nantucket</td>
<td>181</td>
<td>.63</td>
<td>113</td>
<td>1.17</td>
<td>.25</td>
<td>.85</td>
<td>122</td>
</tr>
<tr>
<td>AIY</td>
<td>Atlantic City</td>
<td>81</td>
<td>.53</td>
<td>43</td>
<td>.88</td>
<td>.25</td>
<td>.52</td>
<td>80</td>
</tr>
<tr>
<td>AVP</td>
<td>Wilkes-Barre</td>
<td>89</td>
<td>.60</td>
<td>45</td>
<td>.75</td>
<td>.25</td>
<td>.55</td>
<td>84</td>
</tr>
<tr>
<td>BDL</td>
<td>Hartford</td>
<td>96</td>
<td>.52</td>
<td>50</td>
<td>.88</td>
<td>.25</td>
<td>.57</td>
<td>86</td>
</tr>
<tr>
<td>BGR</td>
<td>Bangor</td>
<td>337</td>
<td>.35</td>
<td>119</td>
<td>2.17</td>
<td>.25</td>
<td>1.37</td>
<td>188</td>
</tr>
<tr>
<td>BGM</td>
<td>Binghampton</td>
<td>130</td>
<td>.45</td>
<td>58</td>
<td>.96</td>
<td>.25</td>
<td>.68</td>
<td>101</td>
</tr>
<tr>
<td>BTV</td>
<td>Burlington</td>
<td>231</td>
<td>.39</td>
<td>89</td>
<td>1.18</td>
<td>.25</td>
<td>1.02</td>
<td>143</td>
</tr>
<tr>
<td>CAK</td>
<td>Akron</td>
<td>340</td>
<td>.28</td>
<td>95</td>
<td>2.37</td>
<td>.25</td>
<td>1.38</td>
<td>189</td>
</tr>
<tr>
<td>EEN</td>
<td>Keene</td>
<td>154</td>
<td>.52</td>
<td>80</td>
<td>1.22</td>
<td>.25</td>
<td>.76</td>
<td>111</td>
</tr>
<tr>
<td>ELM</td>
<td>Elmira</td>
<td>159</td>
<td>.47</td>
<td>74</td>
<td>.83</td>
<td>.25</td>
<td>.78</td>
<td>113</td>
</tr>
<tr>
<td>EWB</td>
<td>New Bedford</td>
<td>149</td>
<td>.47</td>
<td>70</td>
<td>1.18</td>
<td>.25</td>
<td>.75</td>
<td>109</td>
</tr>
<tr>
<td>GON</td>
<td>New London</td>
<td>96</td>
<td>.52</td>
<td>50</td>
<td>.65</td>
<td>.25</td>
<td>.57</td>
<td>87</td>
</tr>
<tr>
<td>HTO</td>
<td>East Hampton</td>
<td>80</td>
<td>.47</td>
<td>38</td>
<td>.75</td>
<td>.25</td>
<td>.52</td>
<td>80</td>
</tr>
<tr>
<td>HVN</td>
<td>New Haven</td>
<td>62</td>
<td>.44</td>
<td>27</td>
<td>.58</td>
<td>.25</td>
<td>.46</td>
<td>72</td>
</tr>
<tr>
<td>HYA</td>
<td>Hyannis</td>
<td>177</td>
<td>.75</td>
<td>133</td>
<td>1.75</td>
<td>.25</td>
<td>.84</td>
<td>121</td>
</tr>
<tr>
<td>ITH</td>
<td>Ithaca</td>
<td>156</td>
<td>.43</td>
<td>67</td>
<td>1.00</td>
<td>.25</td>
<td>.77</td>
<td>112</td>
</tr>
<tr>
<td>IPT</td>
<td>Williamsport</td>
<td>138</td>
<td>.54</td>
<td>74</td>
<td>2.17</td>
<td>.25</td>
<td>.71</td>
<td>104</td>
</tr>
<tr>
<td>LEB</td>
<td>Lebanon</td>
<td>193</td>
<td>.43</td>
<td>84</td>
<td>1.75</td>
<td>.25</td>
<td>.89</td>
<td>128</td>
</tr>
<tr>
<td>MDT</td>
<td>Harrisburg</td>
<td>134</td>
<td>.48</td>
<td>64</td>
<td>1.09</td>
<td>.25</td>
<td>.70</td>
<td>103</td>
</tr>
<tr>
<td>MHT</td>
<td>Manchester</td>
<td>177</td>
<td>.49</td>
<td>87</td>
<td>1.25</td>
<td>.25</td>
<td>.84</td>
<td>121</td>
</tr>
<tr>
<td>MVY</td>
<td>Martha's Vyd</td>
<td>159</td>
<td>.79</td>
<td>125</td>
<td>1.25</td>
<td>.25</td>
<td>.78</td>
<td>113</td>
</tr>
<tr>
<td>ONH</td>
<td>Oneonta</td>
<td>122</td>
<td>.50</td>
<td>61</td>
<td>.83</td>
<td>.25</td>
<td>.66</td>
<td>97</td>
</tr>
<tr>
<td>ORH</td>
<td>Worcester</td>
<td>135</td>
<td>.68</td>
<td>91</td>
<td>1.25</td>
<td>.25</td>
<td>.70</td>
<td>103</td>
</tr>
<tr>
<td>PLB</td>
<td>Plattsburgh</td>
<td>242</td>
<td>.36</td>
<td>88</td>
<td>1.83</td>
<td>.25</td>
<td>1.06</td>
<td>148</td>
</tr>
<tr>
<td>POU</td>
<td>Poughkeepsie</td>
<td>59</td>
<td>.54</td>
<td>32</td>
<td>.50</td>
<td>.25</td>
<td>.45</td>
<td>71</td>
</tr>
<tr>
<td>PVD</td>
<td>Providence</td>
<td>132</td>
<td>.49</td>
<td>64</td>
<td>1.05</td>
<td>.25</td>
<td>.89</td>
<td>101</td>
</tr>
<tr>
<td>Code</td>
<td>City</td>
<td>Fixed Wing</td>
<td>Tilt Rotor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>---------------</td>
<td>------------</td>
<td>------------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distance</td>
<td>Fare Rate</td>
<td>Air</td>
<td>Flight</td>
<td>Delay</td>
<td>Block</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(n mi)</td>
<td>($/n mi)</td>
<td>Fare</td>
<td>Time</td>
<td>(Hr)</td>
<td>Time</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>($)</td>
<td>(Hr)</td>
<td></td>
<td>($)</td>
<td></td>
</tr>
<tr>
<td>PWM</td>
<td>Portland</td>
<td>242</td>
<td>.44</td>
<td>107</td>
<td>1.32</td>
<td>.25</td>
<td>1.06</td>
<td></td>
</tr>
<tr>
<td>RUT</td>
<td>Rutland</td>
<td>178</td>
<td>.47</td>
<td>84</td>
<td>1.68</td>
<td>.25</td>
<td>.84</td>
<td></td>
</tr>
<tr>
<td>SLK</td>
<td>Saranac Lake</td>
<td>223</td>
<td>.37</td>
<td>83</td>
<td>1.75</td>
<td>.25</td>
<td>.99</td>
<td></td>
</tr>
<tr>
<td>UCA</td>
<td>Utica</td>
<td>162</td>
<td>.43</td>
<td>69</td>
<td>1.00</td>
<td>.25</td>
<td>.79</td>
<td></td>
</tr>
<tr>
<td>CHO</td>
<td>Charlottsvil</td>
<td>257</td>
<td>.40</td>
<td>102</td>
<td>1.10</td>
<td>.25</td>
<td>1.11</td>
<td></td>
</tr>
<tr>
<td>CLE</td>
<td>Cleveland</td>
<td>359</td>
<td>.28</td>
<td>99</td>
<td>1.45</td>
<td>.25</td>
<td>1.45</td>
<td></td>
</tr>
<tr>
<td>CMH</td>
<td>Columbus</td>
<td>409</td>
<td>.20</td>
<td>83</td>
<td>1.73</td>
<td>.25</td>
<td>1.61</td>
<td></td>
</tr>
<tr>
<td>CRW</td>
<td>Charleston</td>
<td>379</td>
<td>.33</td>
<td>87</td>
<td>1.42</td>
<td>.25</td>
<td>1.51</td>
<td></td>
</tr>
<tr>
<td>DTW</td>
<td>Detroit</td>
<td>432</td>
<td>.22</td>
<td>95</td>
<td>1.54</td>
<td>.25</td>
<td>1.69</td>
<td></td>
</tr>
<tr>
<td>GSO</td>
<td>Greensboro</td>
<td>392</td>
<td>.22</td>
<td>88</td>
<td>2.14</td>
<td>.25</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td>ORF</td>
<td>Norfolk</td>
<td>254</td>
<td>.21</td>
<td>53</td>
<td>1.22</td>
<td>.25</td>
<td>1.10</td>
<td></td>
</tr>
<tr>
<td>RDU</td>
<td>Raleigh/Dur</td>
<td>366</td>
<td>.22</td>
<td>81</td>
<td>1.52</td>
<td>.25</td>
<td>1.47</td>
<td></td>
</tr>
<tr>
<td>RIC</td>
<td>Richmond</td>
<td>246</td>
<td>.44</td>
<td>167</td>
<td>1.08</td>
<td>.25</td>
<td>1.07</td>
<td></td>
</tr>
<tr>
<td>ROA</td>
<td>Roanoke</td>
<td>344</td>
<td>.28</td>
<td>95</td>
<td>1.33</td>
<td>.25</td>
<td>1.40</td>
<td></td>
</tr>
<tr>
<td>YHZ</td>
<td>Halifax</td>
<td>525</td>
<td>.46</td>
<td>240</td>
<td>2.00</td>
<td>.25</td>
<td>2.00</td>
<td></td>
</tr>
<tr>
<td>YOW</td>
<td>Ottawa</td>
<td>289</td>
<td>.49</td>
<td>141</td>
<td>1.17</td>
<td>.25</td>
<td>1.21</td>
<td></td>
</tr>
<tr>
<td>YQB</td>
<td>Quebec</td>
<td>386</td>
<td>.48</td>
<td>185</td>
<td>1.76</td>
<td>.25</td>
<td>1.53</td>
<td></td>
</tr>
<tr>
<td>YSJ</td>
<td>St. John</td>
<td>451</td>
<td>.47</td>
<td>212</td>
<td>1.72</td>
<td>.25</td>
<td>1.75</td>
<td></td>
</tr>
<tr>
<td>YUL</td>
<td>Montreal</td>
<td>288</td>
<td>.49</td>
<td>141</td>
<td>1.21</td>
<td>.25</td>
<td>1.21</td>
<td></td>
</tr>
<tr>
<td>YXU</td>
<td>London</td>
<td>351</td>
<td>.49</td>
<td>172</td>
<td>1.60</td>
<td>.25</td>
<td>1.42</td>
<td></td>
</tr>
<tr>
<td>YYYZ</td>
<td>Toronto</td>
<td>310</td>
<td>.48</td>
<td>147</td>
<td>1.42</td>
<td>.25</td>
<td>1.28</td>
<td></td>
</tr>
</tbody>
</table>
REFERENCES

Harvey, Greig, "Airport Choice in a Multiple Airport Region," Transportation Research, 1987.
NASA Ames Research Center, State/Regional Tiltrotor/Vertiport Feasibility Studies Data Package, June 1, 1989.

