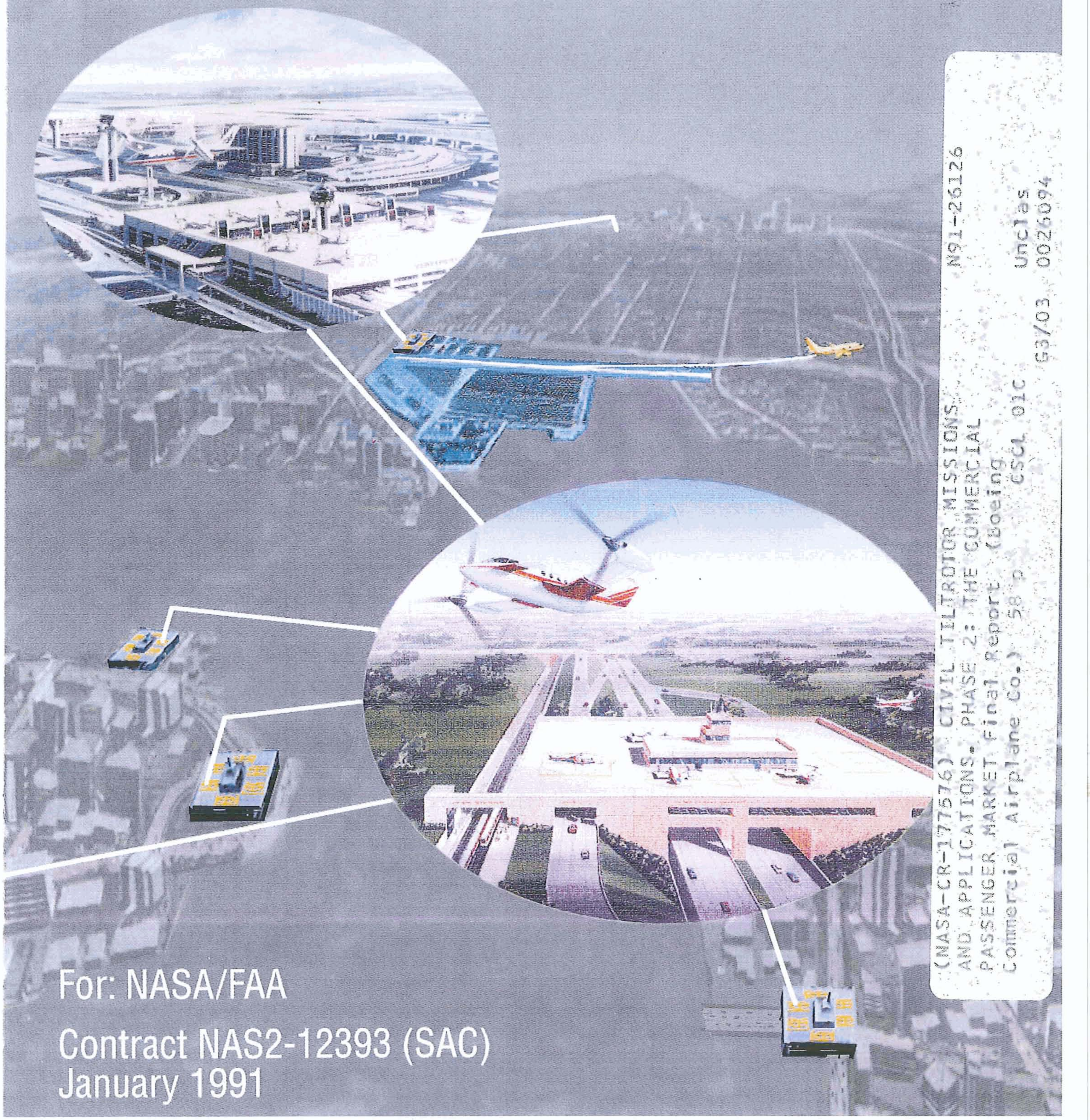
Civil Tiltrotor Missions and Applications Phase II:

The Commercial Passenger Market

NASA-CR-177576



For: NASA/FAA

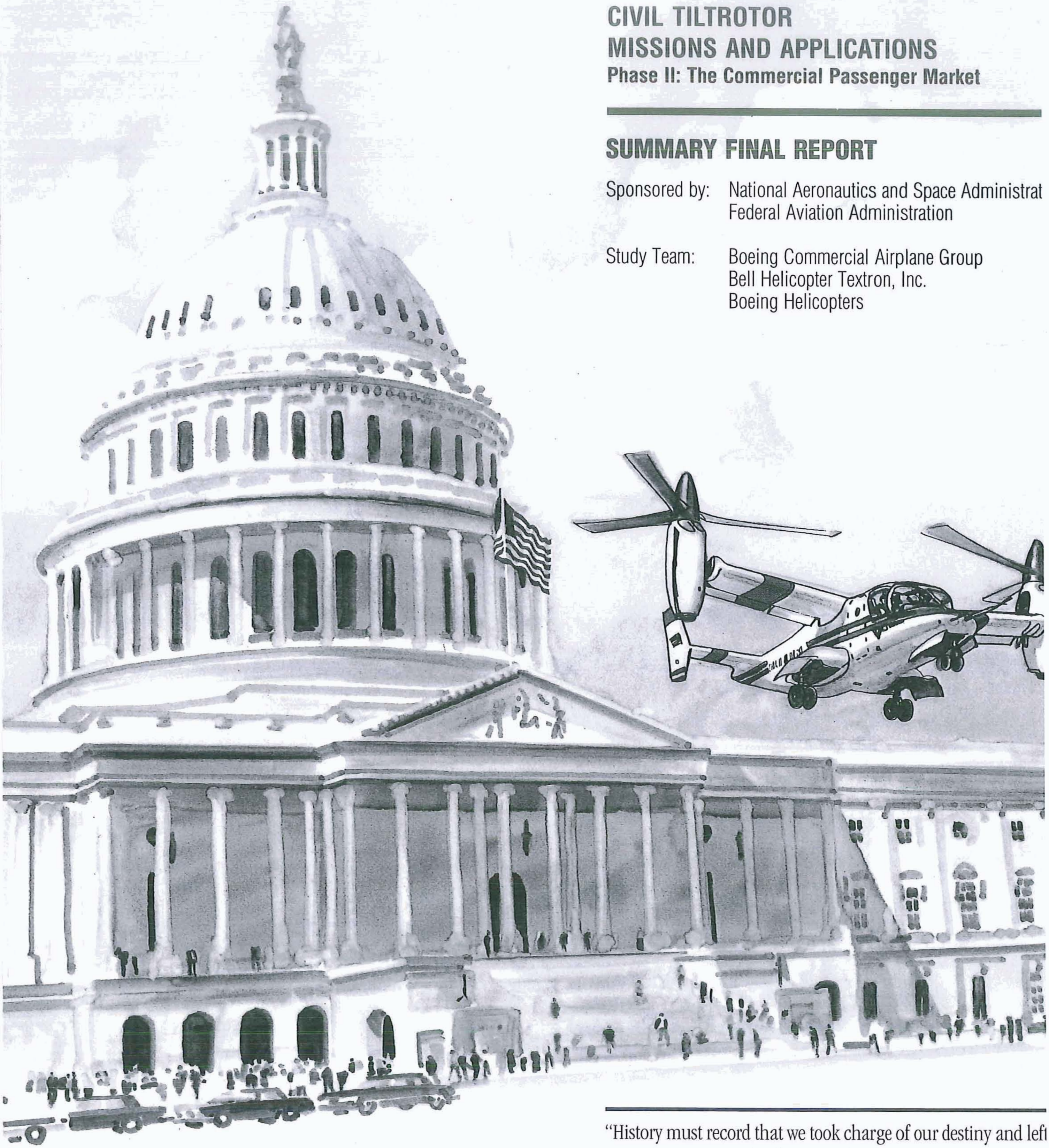
Contract NAS2-12393 (SAC)
January 1991

CIVIL TILTROTOR MISSIONS AND APPLICATIONS
Phase II: The Commercial Passenger Market

SUMMARY FINAL REPORT

Sponsored by: National Aeronautics and Space Administrat
Federal Aviation Administration

Study Team: Boeing Commercial Airplane Group
Bell Helicopter Textron, Inc.
Boeing Helicopters



"History must record that we took charge of our destiny and left a new generation with a better environment, a higher quality of life, and greater opportunities.

To achieve this goal, transportation and transportation policy can be—must be—a vital agency for change."

George Bush
President of the United States

CR No. 177576
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Statement from the Industry Study Team

February 1991

The U.S. aviation system is generally regarded as a marvel of technology: safe, reliable, efficient, and convenient. But congestion—in the air, at the airport, on the roads leading to the airport—is serious, and worsening.

> *"Twenty-one primary airports now each experience more than 20,000 hours of annual delays at a yearly cost to airlines and U.S. businesses of at least $5 billion; by 1997, 33 airports are forecast to experience this level of delay."*
>
> Moving America—National Transportation Policy

The United States leads the world in tiltrotor technology and experience. The commercial tiltrotor is an evolutionary step in turning that technology into a national asset that contributes to relieving congestion—a national dilemma—while creating high-value jobs and a ready export market. This report concludes:

- A commercial tiltrotor is both technically feasible and economically competitive.
- The market potential for short-haul passenger operations is strong.
- Commercial tiltrotors can extend the useful life of existing airports and preserve service to small aiports.
- Prospective operators demand proof of the safety, efficiency, and environmental soundness of the commercial tiltrotor.
- A market-responsive vehicle is not, by itself, sufficient. Commercial tiltrotors require an enabling air and ground infrastructure that is designed to complement their unique capabilities.

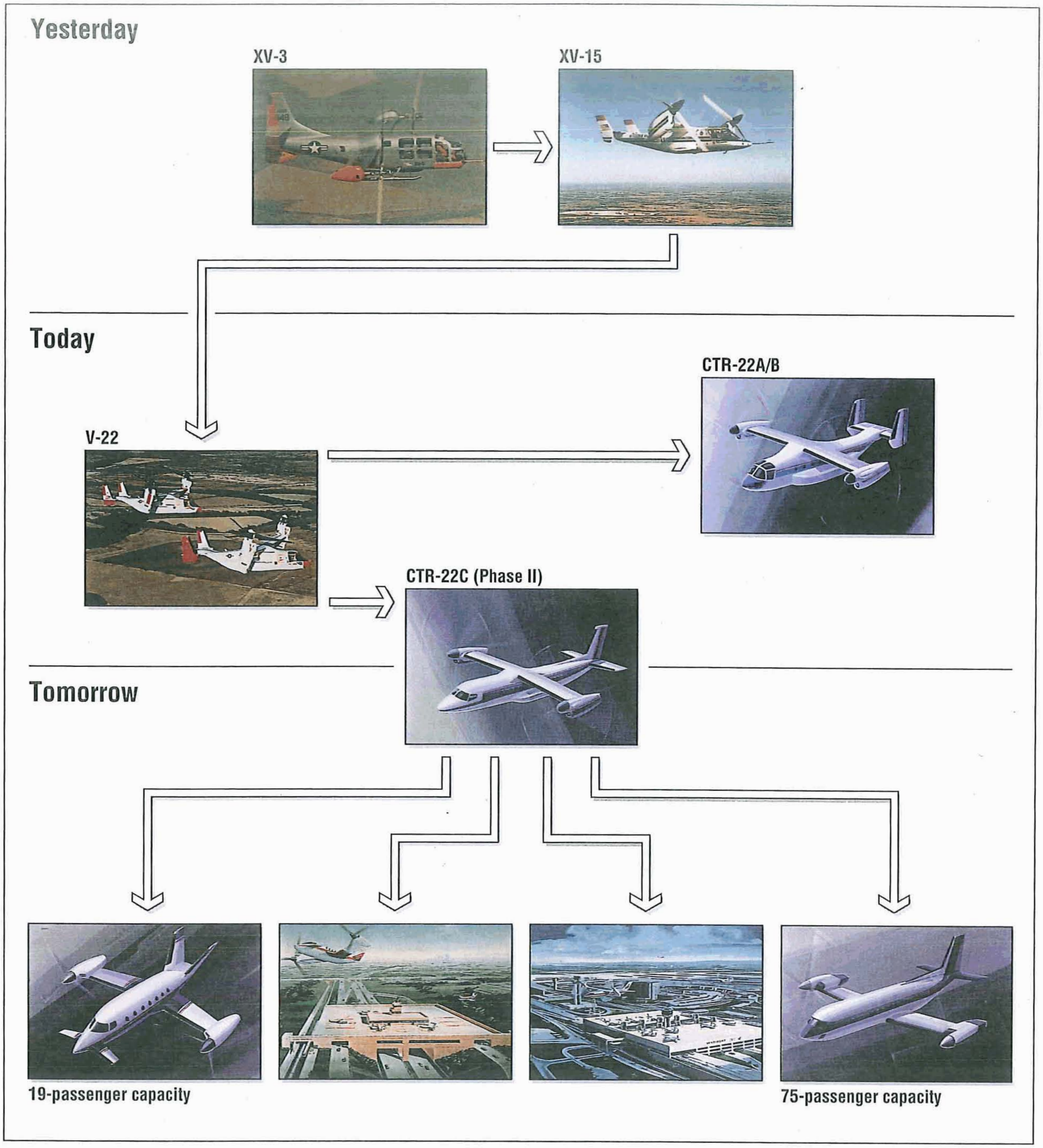
The role of the commercial tiltrotor in the national transportation plan is unclear. Without strong Federal leadership and commitment, the private and local sectors cannot do what they do best: take the initiative and "make it happen." Neither private industry nor local government has control over airspace and interstate commerce. The Federal government has the prerogative to foster the air and ground infrastructure needed for a practical commercial tiltrotor system.

Left to "business as usual," decades could pass before a nonconventional solution like the commercial tiltrotor is seriously considered. In the meantime, congestion of our air transportation system consumes $5 billion of national resources each year, while eroding the mobility of our citizens. For the tiltrotor to contribute to a solution, innovative thinking and dedicated leadership are required. One approach would be to form a public-private partnership to "jump start" commercial tiltrotor evolution.

This study outlines a commercial tiltrotor technology validation process that could create a functioning system for the United States by the year 2000. The first step is a 4-year public-private partnership, with Federal government participation. By January 1995, the partnership would decide whether creating a commercial tiltrotor system is technically feasible, economically attractive to private industry, and in the national interest. At that point, the partners would revert to their traditional roles.

> *For half of the $4- to $6-billion cost of a single new airport, an entire network of 12 urban vertiports, including the cost of 165 40-seat tiltrotor aircraft, could be installed in the congested corridor between Boston and Washington, D.C., serving 12 million passengers per year.*

TILTROTOR GENEOLOGY



CONTENTS

OVERVIEW

Introduction

Results of Phase II of the NASA/FAA Civil Tiltrotor Study are summarized in this book, under the following headings:

Overview. Presents study findings and recommendations (pages iv through vi).

Background. Discusses issues accelerating and impeding commercial tiltrotor development, the history of tiltrotors in the U.S., results of the 1987 Phase I FAA/NASA/DOD study, and considerations underlying the Phase II study (pages 1 through 10).

Tasks I and V: Market Evaluation. Assesses the market and potential uses of the commercial tiltrotor, requirements for vertiports, and economics of the commercial tiltrotor (pages 11 through 26).

Task II: Commercial Standards and Technology Benefits. Explores technology improvements and the benefits of applying commercial standards in the design of a civil tiltrotor (pages 27 through 37).

Task IV: Operations Analysis—Approach and Landing Profiles. Discusses piloted simulations of the commercial tiltrotor (pages 38 through 43).

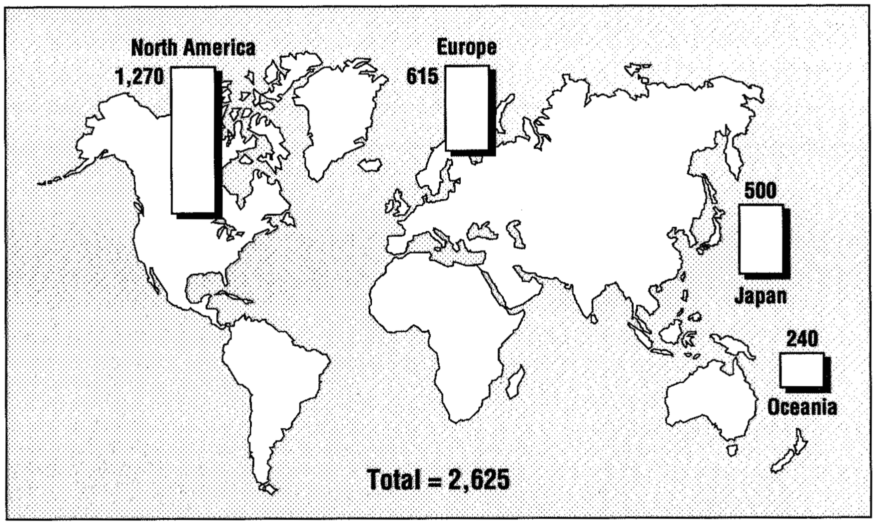
Task VII: Flight Validation Plan. Recommends a 4-year public/private partnership and presents a plan to develop a national tiltrotor transportation system by the year 2000 (pages 44 through 49).

Findings

A commercial tiltrotor is technically feasible and economically competitive. A market-responsive aircraft could be designed, and the cost/price loop could be closed. Tiltrotor aircraft could be made available for an operating tiltrotor system by the year 2000. A "turn-of-the-century" commercial tiltrotor would be based on ongoing research and experience gained in designing, building, testing, and producing the military V-22 tiltrotor (the "Osprey").

Commercial tiltrotors can extend the useful life of existing airports and preserve service from small airports to congested hub airports. Tiltrotors operating to and from vertiports at congested airports could increase hub airport capacity by diverting short-haul travelers to the on-airport vertiport, thereby freeing up runway and approach slots for more efficient, longer flights by larger jets and encouraging continued air service to small communities. Additionally, a network of off-airport vertiports could divert urban area to urban area travelers away from crowded hub airports entirely, further reducing airport congestion and traffic on roads leading to the airport. Finally, a network of on-airport and off-airport vertiports could postpone or eliminate expensive and environmentally difficult airport expansion.

Year 2000 Market Demand for a 40-Seat Civil Tiltrotor (Passenger Service Only)



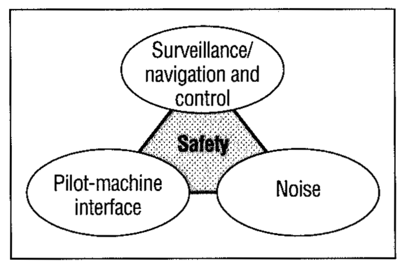
A market-responsive vehicle is, by itself, not sufficient. The commercial tiltrotor needs an appropriate air/ground infrastructure to be of practical service. Purposeful, coordinated development of infrastructure is essential for industry to proceed with commercial tiltrotor development.

Three technical issues are potential obstacles:

- Community noise.
- Human factor-based pilot controls for the commercial mission.
- Vertiport airspace navigation, surveillance, and control.

These issues are interrelated and most critical during the few seconds before landing and after takeoff. They must be resolved before tiltrotors can operate in the urban environment.

Potential Technical Obstacles Are an Integrated Challenge



The market potential for the commercial tiltrotor is strong for short-haul passenger operations. Half of the existing commercial airline fleet is used for service under 500 nmi. Tiltrotors providing such short-haul service could reduce serious congestion problems—and produce a global market demand for more than 2,600 tiltrotors, more than half of which would be exported.

Prospective operators demand proof that commercial tiltrotors are safe, efficient, and environmentally sound. The marketplace will not purchase promising new technology until that technology has been proven.

Three nontechnical issues need to be resolved:

1. National recognition and endorsement of the tiltrotor as a preferred means of relieving congestion.
2. National leadership and a Federal plan to introduce the tiltrotor into the nation's transportation system.
3. New thinking—a new, creative, integrated approach.

A 4-year public-private partnership is proposed to meet these needs. The partnership would work to develop an efficient, cost-effective national tiltrotor transportation system by the year 2000.

"Countries that invest more, tend to be those with the highest rates of growth in productivity."

Report of the President's Commission on Competiveness

Recommendations

Initiate a national plan, leading to implementation of an initial commercial tiltrotor transportation network by the year 2000, with specific actions shown below:

	Action	Purpose
General	1. Form a public/private partnership in 1991 to pursue a national commercial tiltrotor plan.	Bring diverse responsibilities together.
	2. The Federal Department of Transportation take a leadership role in partnership.	Ensure tiltrotor's integration into the national transportation system.
	3. Continue NASA/FAA/industry cooperation for commercial tiltrotor developments.	Provide momentum for other technology applications.
NASA	1. Develop commercial technology based on: ■ Aircraft noise. ■ Pilot-machine interface. ■ Vertiport terminal area IFR navigation, surveillance, and control.	Address these potential technical barrier issues in conjunction with the FAA.
	2. Sponsor technology validation program, using V-22, upgraded XV-15, and flight simulator assets.	Establish relationship between tiltrotor technology requirements and essential public credibility and acceptance.
	3. Reduce technical risks and costs through improved materials and design technology.	Provide technology options that can enhance product values through longer market life, lower costs, and enhanced safety.
	4. Initiate research to extend tilitrotor technology base to civil-optimized requirements.	Lay technical foundation for future commercial and other civil applications.
FAA	1. Develop operational standards for: ■ Community noise. ■ Pilot-machine interface. Develop the capability for: ■ Vertiport terminal area IFR, navigation, surveillance, and control.	Address these potential technical barrier issues, in conjunction with NASA.
	2. Develop vertiport terminal instrument procedures (TERPs) that exploit tiltrotor's unique operational capability.	Ensure vertiport design and access standards are compatible with air traffic control capability and community noise limitations.
	3. Ensure the national airspace system (NAS) is capable of supporting CTRs en route requirements.	Minimize en route delays.
	4. Advocate and support the flight technology validation program.	Establish essential public credibility and acceptance of commercial tiltrotor operations.
	5. Provide FAA vertiport study grants to key components of initial commercial tiltrotor system.	Focus planning and preparation on key cities and congested airports.
	6. Expedite acquisition of V-22 engineering test data.	Minimize duration of initial civil certification process.

Issues Accelerating Commercial Tiltrotor Development

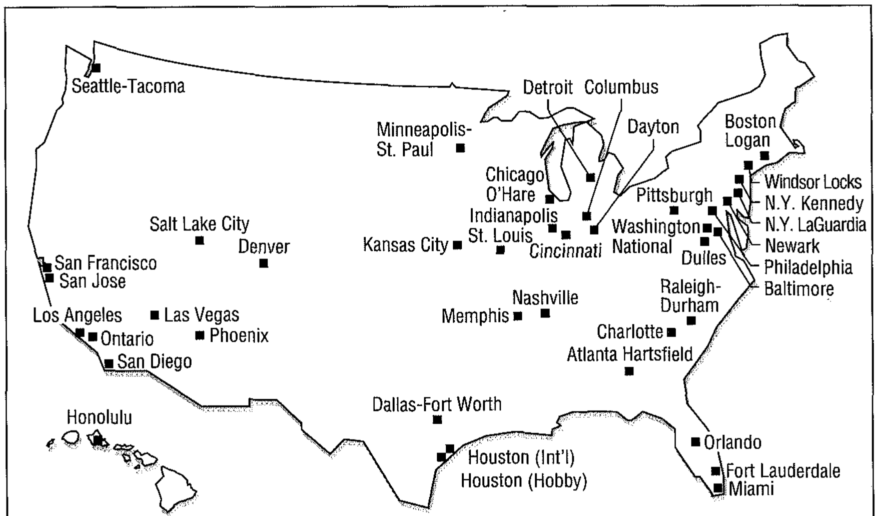
A number of issues drive the development of the commercial tiltrotor as an integral part of a comprehensive national transportation system.

National transportation system need: improved mobility

Studies project large increases in the demand for air travel by the year 2000:

- 74% increase in passenger enplanements in the United States.
- 32% increase in the number of jet transports in the United States.

41 Airports Forecast to Exceed 20,000 Hours of Annual Air Carrier Delays in 1998



Source: FAA 1990-91 Aviation System Capacity Plan

Among today's most congested airports are the 10 busiest airports in the United States, which together handle a third of all passenger enplanements. Capacity shortfall airports are prime candidates for onsite vertiports.

Yet only three runways will be added to these busiest airports before the turn of the century, and only one new airport is expected to be built (at Denver). The problems are the pervasive consumption of land, environmental impact, opposition to aircraft noise, and cost.

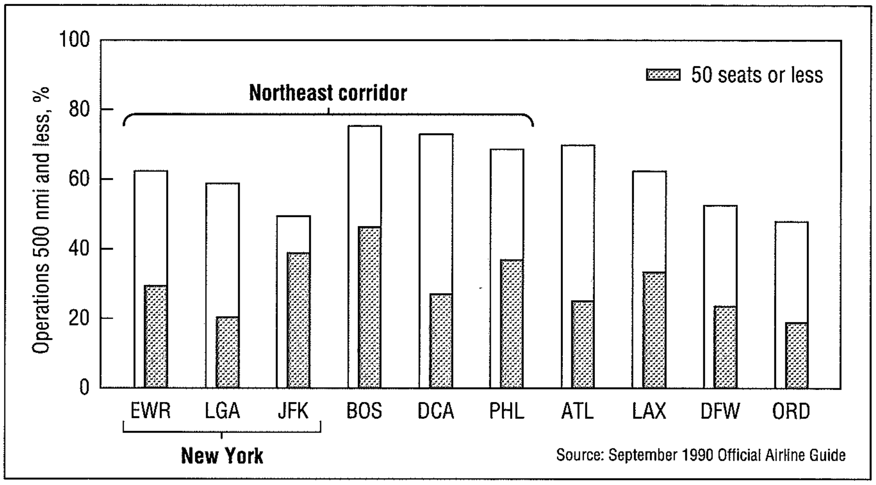
More airplanes will be competing for increasingly scarce runway slots. Passengers will experience delays more often and for longer periods of time. Delays are already a serious problem, especially in the crowded northeast corridor of the United States. Delays at the airport are compounded by worsening delays on roads leading to the airport.

Airport Land Usage

O'Hare	11 mi^2
Dallas-Ft. Worth	27 mi^2
Denver (new)	50 mi^2

A major contributor to airport congestion is that many people are flying relatively short distances on relatively small aircraft.

Major Hub Airport Capacity Is Consumed by Short Haul, With Small Airplanes (Weekdays)



"In FY 1988, regional and commuter air carriers accounted for 6% of total passenger traffic at Boston Logan..."

MASSPORT Prospectus, October 1988

The commercial tiltrotor aircraft can help reduce airport congestion and traffic delay problems by—

- Using on-airport vertiports to siphon off short-haul connecting travelers, thereby freeing runway slots for larger aircraft.
- Using off-airport vertiports for urban area to urban area and city center to city center service, diverting travelers away from crowded hub airports and their access roads.
- Allowing passengers to experience portal-to-portal time savings, thereby improving their mobility and efficiency.
- Extending a congested airport's useful life without major investment in air-side facilities.
- Enhancing capacity with tiltrotor aircraft, expected to be environmentally friendly, compared to other means of enhancing capacity.
- Maintaining air service to smaller communities, preserving access and mobility benefits to those communities.

Worldwide congestion relief

While airport congestion problems are severe in the United States, they are worse abroad. European and Japanese authorities have not only expressed great interest in the timely availability of technology to relieve a heavily burdened transportation system, they also are investing in their own tiltrotor/tiltwing technology development (additional information on page 9).

Economics

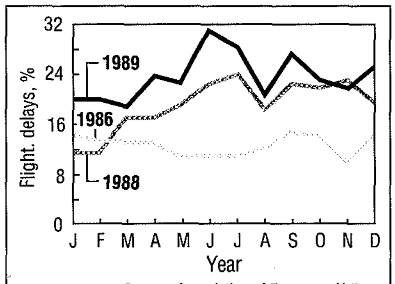
A commercial tiltrotor system has the potential to produce economic benefits at the national, state, and local levels.

Large export market. The market opportunity portion of this study estimates an American commercial tiltrotor could generate $28 billion in exports in its first 10 years of availability, assuming timely development of the commercial tiltrotor (CTR) aircraft and an appropriate air and ground infrastructure.

National economic development. Manufacture of the CTR aircraft and development of supporting vertiports has a positive effect on national employment. Besides the direct CTR and vertiport development jobs, employment diversification results as manufacturing and service industries develop around the new hubs of transportation (vertiports). Quantifying national economic development was not the principal focus of this study, but it can be noted that industry would have to invest at least $2 billion more to produce the United States' first commercial tiltrotors. Additionally, an initial network of 25 vertiports would require private or local investment of $1 billion to $2 billion. Relatively speaking, vertiports are economical to build and conserving of land—as little as $40 million and 5 acres. A system of vertiports would serve to distribute the demonstrated favorable economic impact of urban airports throughout the community. Considering multiplier effects, a study done for the Department of Commerce concluded the increased national economic activity would be approximately $80 billion for every 1,000 commercial tiltrotors produced.

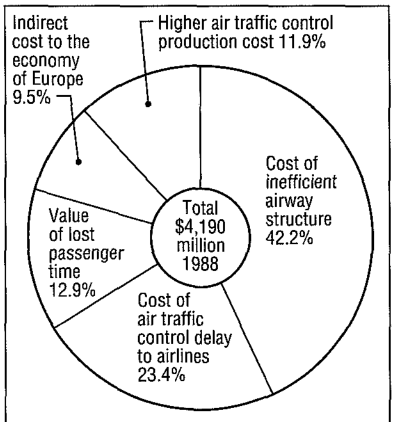
Extended effective life for airports. This study suggests that the CTR could enjoy a substantial short-haul and commuter market. Much of this traffic could be diverted to tiltrotors, which do not require runways. Freed-up runway slots can be made available for more efficient longer flights by larger jets. Expense and land use can be minimized by colocating with compatible uses and by locating over freeways, railroad yards, piers, etc. Small urban airports might be suitable in lieu of vertiports in some locations. Expensive construction of new runways and new airports—environmentally difficult in most urban areas—can be postponed or eliminated. The useful life of crowded airports can thereby be extended.

International Short- and Medium-Haul Departure Delays of More Than 15 Minutes



Source: Association of European Airlines

Cost of Air Traffic Control Inefficiency in Europe in 1988



Source: Association of European Airlines

Capitalizing on the national investment

The combined postwar investment of the U.S. aerospace industry and the U.S. Government in tiltrotor research and development exceeds $2.5 billion. From this foundation, tiltrotor technology is ready to move to the next logical phase, which includes two separate but complementary activities: (1) initiation of production of a military version to meet the government's needs and (2) an interative program to demonstrate tiltrotor technology to the commercial marketplace.

Although there are striking differences between commercial and military tiltrotor aircraft, there is no doubt that ultimate efforts toward development of a commercial version will lead to design improvements that can improve the quality and performance of military tiltrotors. Likewise, military production aircraft may contribute to "proving" the tiltrotor concept by demonstrated success. Taken together, the safety, reliability, and cost effectiveness of tiltrotors can be verified.

Commercial airlines have underscored the importance of demonstrating and validating the commercial viability of the tiltrotor. They have expressed reluctance to commit to a comparatively revolutionary vehicle such as the tiltrotor until the technical, cost, and operational system risk issues have been satisfactorily resolved.

Continued evaluation of the potential civil applications of the tiltrotor and continued development of tiltrotor systems and infrastructures is therefore required. This continued effort, coupled with the experience gained with production V-22 aircraft, can help establish the requisite levels of confidence in the commercial marketplace and a basis for a decision leading to production of the civil tiltrotor.

Beyond congestion relief, civil tiltrotors could be available for service in these areas:

- Improved air travel and access to rural and isolated areas.
- Disaster relief.
- Public service (police, fire, and emergency medical services).
- Coast Guard, border patrol, and drug interdiction.

"The fax machine is American in invention, technology, design and development. Yet not one fax machine offered for sale in the U.S. today is American-made."

Peter Drucker
Wall Street Journal
November 20, 1990

The commercial tiltrotor concept supports national transportation policy themes:

" ■ Maintain and expand the nation's transportation system.

■ Foster a sound financial base of transportation.

■ Ensure the the transportation system supports public safety and national security.

■ Protect the environment and the quality of life.

■ Advancing U.S. transportation and expertise."

—Moving America. DOT, 1990

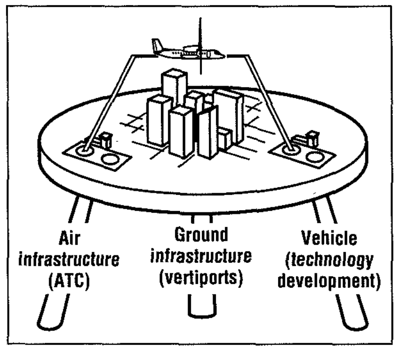
Issues Impeding Commercial Tiltrotor Development

Developing a commercial tiltrotor system involves three major activities:

1. Adapting the air traffic control system to exploit the tiltrotor's capability.
2. Creating a ground infrastructure separate from airport limitations and constraints.
3. Validating the technology for commercial applications and developing the aircraft itself.

All three activities must take place before a tiltrotor system is practical; one or two is not sufficient. They have to be undertaken simultaneously if a system is to develop within the next decade. The findings, conclusions, and recommendations presented on pages iv through vi of this report focus on these activities. Making them happen requires resolution of both technical and nontechnical issues.

Supporting Elements of Commercial Tiltrotor System



Technical issues

Technical issues fall into two categories: those that are truly barriers to a commercial tiltrotor system ("potential obstacles") and those that enhance and expand the tiltrotor's market attractiveness ("enabling technologies").

Potential obstacles:

- *Noise (external).* If commercial tiltrotors are to provide "close to the community" air transportation, they must have access to an urban vertiport infrastructure. Tiltrotors will not be allowed access if the environmental impact, particularly noise, outweighs the benefits of CTR service. Preliminary results of NASA/Bell XV-15 noise studies show promising projections for the noise footprint of a commercially sized vehicle, but more research is needed. Particular emphasis should be on investigation of the effect, consistent with safe operation, of steep approach and departure angles on footprint area.
- *Vertiport terminal area navigation, surveillance, and control.* A prerequisite to commercial tiltrotor success is reliable all-weather operations. The technologies of microwave landing systems, satellite global positioning systems, and radar must be integrated to form an urban vertiport air traffic control system.
- *Human factor-based pilot controls.* Commercial tiltrotors will operate in the vertical (helicopter) mode for only a minute or two each flight. However, those are the minutes of flight when safety is most crucial. The most natural interaction between pilot and aircraft—the man/machine interface—must be researched and the most appropriate control devices developed for this new class of aircraft. Pilot workload, experience of the pilot community, crew station design, and instrumentation displays are important design considerations.

Enabling technologies:

- *Air traffic control.* The current airport and airway ATC—designed around the characteristics and limitations of fixed-wing aircraft—needs to be modified to allow exploitation of the unique capabilities of a commercial tiltrotor.
- *Emissions.* On a per-passenger basis, aircraft are less polluting than automobiles. Commercial tiltrotors may actually contribute to a net decrease in urban pollution by shortening ground access time.
- *Payload fraction.* Means of reducing aerodynamic drag, lowering empty weight, improving energy efficiency, and minimizing download in the vertical mode are critical to profitable commercial operation and need to be investigated.
- *Gearbox.* The V-22 drivetrain has sufficient growth capability to handle commercial designs of the V-22 size. However, the reliability, safety, and efficiency of new gearbox designs tailored to the specific needs of commercial operations should be explored.
- *Rotor design.* Neither V-22 nor XV-15 rotor systems were designed with commercial requirements in mind. New technology blades could clearly reduce cabin and footprint noise and perhaps increase cruise efficiency as well.
- *Noise (internal).* Noise levels inside the tiltrotor can be reduced to the same level as the noise inside a commercial turboprop airplane. A combination of active and passive noise damping will be used.
- *Safety and certification.* Commercial certification must be specifically tuned for the capabilities and requirements of the commercial tiltrotor.
- *Defining CTR configuration.* If a commercial tiltrotor is to be ready to enter commercial service in the year 2000, the design variables of the CTR must be "frozen" by mid-1995. The partnership must concentrate on defining the best possible configuration by that time.
- *Economics of CTR.* Analysis conducted in Phase I and Phase II of this study indicate the commercial tiltrotor will be economically competitive. Analyses should be continued to validate commercial tiltrotor markets and operating economics.

Nontechnical issues

The nontechnical issues pertain to public interest and policy questions that are subject to debate and consensus. They involve consideration of the fundamental roles of government and the private sector in promoting U.S. competiveness in the high-technology global marketplace and in developing new transportation infrastructure.

- Is the Federal Government prepared to provide a fostering environment through national policy...to lead?
- Can a way be found to bring the investment strength of the private sector into an off-airport vertiport network?

- What is the appropriate funding relationship between the public interest (both Federal and local government) and the private sector?
- How is acceptance by the community, operator, and passenger to be achieved?

History

Research into tiltrotor technology began in the 1940s. A commercial tiltrotor would be a direct descendant of the XV-3, XV-15, and V-22.

XV-3. Built in 1953, this experimental aircraft flew until 1966, proving the fundamental soundness of the tiltrotor concept and gathering data about technical improvements needed for future designs.

XV-15. In 1972, with funding from NASA and the U.S. Army, Bell Helicopter Textron started development of the XV-15, a twin-engine tiltrotor research aircraft. Two aircraft were built to prove the tiltrotor design and explore the operational flight envelope for military and civil applications. The XV-15s have demonstrated excellent handling, low pilot workload, and good ride qualities; they continue to be used as experimental testbeds.

V-22. In 1981, using experience gained from the XV-3 and XV-15, Bell Helicopter Textron and Boeing Helicopters began developing the V-22 "Osprey," a twin-turboshaft military tiltrotor aircraft. Six flying full-scale development aircraft are to be built; four had flown at year-end 1990.

FAA/NASA/DOD study (Phase I)

In 1985, NASA, the FAA, and the DOD sponsored Phase I of the civil tiltrotor study, performed by an industry team from Boeing Commercial Airplanes, Bell Helicopter Textron, Inc., and Boeing Helicopters. This study resulted from a memorandum of agreement (MOA) among the FAA, NASA, and the DOD. The general objective of the MOA was:

> "...to assess the broader implications of the V-22 aircraft development to the nation as a whole. This includes the potential for other versions and sizes, both civilian and military, civil certification issues, civil production impact on the defense industrial base and any indirect technology spinoffs..."

Market characteristics, market size, and aircraft requirements were investigated; six aircraft sizes were postulated and studied. The largest market identified was high-density passenger service, using a 36- to 45-seat tiltrotor. Phase I of the study was completed in mid-1987.

This first "broadbrush" look at civil tiltrotors examined—

- Various tiltrotor configurations, including V-22 derivatives and all-new designs. Six configurations (8- to 75-passenger) were studied.
- Potential markets, including high- and low-density commercial passenger travel, resource development, public service, corporate and executive travel, and cargo and package express service.
- Economics, including operating costs, maintenance costs, cost to build, and market-based pricing.
- Other issues such as certification, ride comfort, vibration, noise, emissions, technology spinoffs, and contribution to the national transportation system.

Phase I of the study made these conclusions about the market for a commercial tiltrotor:

- The market potential could be large, especially in high-density air travel corridors where congestion relief is needed. A 39-passenger version with a pressurized fuselage and conventional passenger amenities had the largest market potential.
- The civil tiltrotor would be competitive with fixed-wing aircraft where convenience and time-savings are important.
- The primary market is in North America.

Additional study was advised to examine several risk areas:

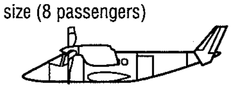
- Technical (pressurized fuselage, competitive cost designs, aerodynamic improvements, higher performance).
- Certification (engine out and failure mode criteria, cockpit operations, all-weather operations).
- Infrastructure (vertiport design and location, adoption into the national aerospace system).
- Operational characteristics (route proving, terminal access).
- Marketing (public perceptions of safety, noise, comfort, and economic competitiveness, developing supporting infrastructure).

The study recommended a four-step process to develop a national tiltrotor transportation system:

1. Continue to develop tiltrotor technology:
   - Reduce risks and costs through design concepts, materials, and production methods.
   - Optimize aerodynamics and configurations.
   - Validate key tiltrotor technologies.
2. Plan and develop infrastructure:
   - Place vertiports at convenient locations in urban areas.
   - Develop new terminal instrument procedures to take advantage of precision navigation equipment.

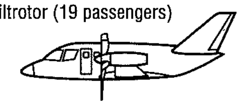
CTR Family

CTR-800
XV-15 size (8 passengers)



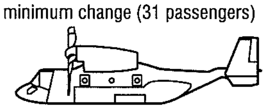
- New high-wing design

CTR-1900
New tiltrotor (19 passengers)



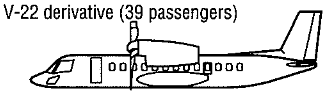
- New low-wing design

CTR-22A/B
V-22 minimum change (31 passengers)



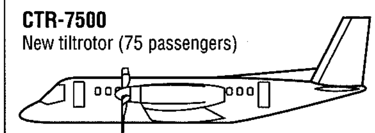
- Nonpressurized fuselage

CTR-22C
V-22 derivative (39 passengers)



- New pressurized fuselage

CTR-7500
New tiltrotor (75 passengers)



- New low-wing design

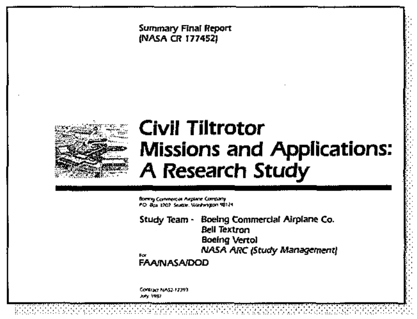
- Integrate tiltrotor transportation into the national airspace system.
- Develop certification criteria for powered lift and develop airworthiness criteria.

3. Develop flight technology demonstration plan:
   - Identify key technologies.
   - Identify vehicle candidates.
   - Support certification criteria.
   - Define relationship to infrastructure needs.
   - Develop financial options and schedule.
4. Take near-term actions:
   - Continue Government-industry cooperation.

Phase I Study results were reported in a Summary Final Report in 1987 to strong congressional and industry interest. Since then, additional activities have occurred:

- A European organization (EUROFAR) is continuing work on a commercial tiltrotor, primarily financed by $30 million from five national governments.
- A Japanese organization (Ishida) is developing a tiltwing aircraft, sized to serve both executive and transport markets.
- A Japanese organization is advocating the development of a network of 600 heliports/vertiports in Japan, and has already developed 20 of them.
- A California organization (Magnum Tiltrotor) announced plans for a prototype executive transport-size tiltrotor.
- The FAA developed interim airworthiness criteria for powered lift aircraft.
- The FAA established the National Civil Tiltrotor program office as a focus for all civil tiltrotor activities: Government, industry, and public (now renamed "Vertical Flight Special Program Office," with an expanded charter).
- DOT published its National Transportation Policy, which calls for short-haul air travel congestion relief by vehicles such as the commercial tiltrotor.
- More than a dozen local and regional tiltrotor/vertiport feasibility studies have been initiated in the United States and Canada.
- NASA and the FAA extended the study program for a second phase, the results of which are summarized in this document.

Phase I Report



Summary Final Report
(NASA CR 177452)

Civil Tiltrotor
Missions and Applications:
A Research Study

Boeing Commercial Airplane Company

Study Team - Boeing Commercial Airplane Co.
Bell Textron
Boeing Vertol
NASA ARC (Study Management)

For
FAA/NASA/DOD

Phase II Study Considerations

Air transportation system problems today are caused by aviation's success and reflect a lack of low-cost, low environmental impact solutions. These problems include:

- Air congestion. Airport congestion is the direct result of acceptance by the general public of routine, affordable air travel, stimulated by economic growth, increasingly globalized industry, and the shift away from a regulated air system. With air travel projected to double by 2010, congestion can only worsen.
- Ground congestion. Traditional large airports concentrate people. Traffic-dense roads feeding airports are increasingly clogged because of increased air travel. Development around airports also helps concentrate traffic, worsening congestion.
- Conventional solutions are limited. Extensive construction of large new airports and interstate highways is not realistic. Increasing frequency and size of aircraft may provide short-term capacity increases but they also directly increase noise.

Innovative approaches are needed for the long term. This report documents the potential of the commercial tiltrotor as a cost-effective means of reducing airport congestion and airport ground access delays, with low environmental impact.

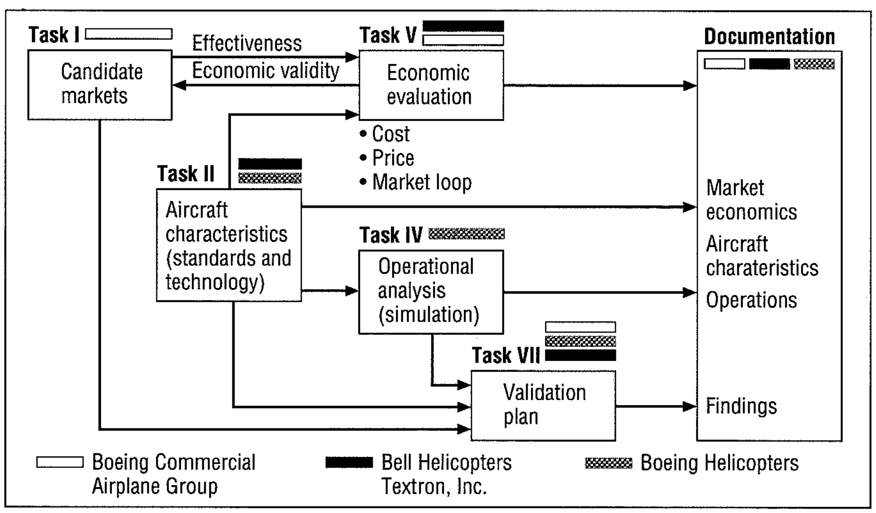
"This industry (transportation) is a focal point for technology innovations."

Samuel Skinner, Secretary,
U.S. Department of Transportation

Phase II study tasks

Of the seven tasks performed for the original Phase I study, two (Task III, facility requirements and Task VI, technology spinoffs) were not reevaluated. The remaining five tasks needed further analysis in Phase II. An integrated plan was followed to analyze these strongly interrelated tasks, as shown below.

Phase II Study Plan



The balance of this report presents the results of the five study tasks, in this order:

Tasks I and V:	Market evaluation
Task II:	Aircraft characteristics
Task IV:	Operations analysis (commercial standards and technology benefits)
Task VII:	Flight validation plan

TASKS I and V: MARKET EVALUATION

The Phase II study was guided by the findings of Phase I and concentrated on commercial tiltrotor (CTR) passenger operations. The team examined potential users, infrastructure requirements, economics, and system operation to form an overall evaluation of the CTR's market attractiveness.

Market Assessment

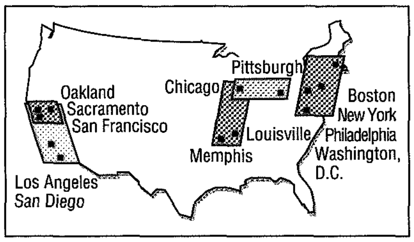
To establish a "real world" perspective to the market evaluation, interviews were conducted with representatives of:

- FAA regional offices.
- Key airlines.
- Air package express carriers.
- Local and state government bodies (airport authorities, cities, state departments of transportation, councils of government, and regional planning authorities).
- Private sector (developers and consultants).

The results of these discussions are incorporated throughout this report, but a summary of opinions expressed is listed here, since they represent the realities of current perceptions about potential tiltrotor service:

- Unless carefully put forward, the CTR will be seen as an "elitist" vehicle designed to serve a special clientele. The public needs to see the CTR as a cost-effective, safe, reliable, accessible—and therefore desirable—alternative to other transportation modes.
- The CTR is seen as being most similar to a helicopter, and helicopters are unwanted in major urban areas, mainly because of their intrusive noise and some safety concerns. There is some openess to a CTR as a safe, quiet, "good neighbor" vehicle for use in urban vertiports, but only if their operation is divorced from the operation of helicopters.
- In many cases, restrictive zoning is in place to prevent incursion of "undesirable" uses. Care must be taken to involve city governments and vertiport neighborhoods as partners early in the comprehensive planning process to allow CTR use.
- Unanimously, airports are seen as vital to local trade and future economic growth. At the same time, most communities do not support expansion of existing in-city airports, preferring new airports to be located far from city limits.

Civil Tiltrotor User and Infrastructure Survey



Quotations from field surveys:

"I will operate a CTR only if I can make money with it."

"The CTR must overcome the bad public perception—and the poor operational experience—of the helicopter."

"The CTR makes a lot of sense conceptually, but there are still a lot of unanswered questions."

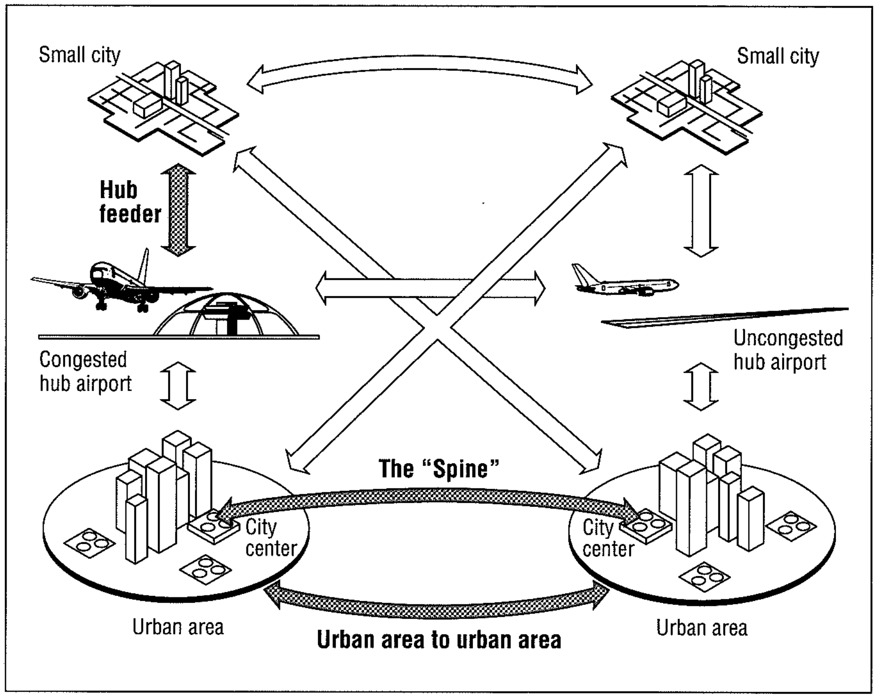
Key Operating Requirements

- Free of fixed-wing ATC restrictions.
- IFR operational capability required.
- Airspace must be made available.
- Safe and reliable aircraft.
- Competitive tiltrotor price and operating economics.

Potential Usage

Nine candidate markets were investigated, three of which were identified as having the greatest potential for a successful CTR system (shaded arrows in figure below):

Tiltrotor Markets



Urban Area to Urban Area. Examples of urban area to urban area markets are the Northeast Corridor, the Dallas-Ft. Worth–Houston Corridor, and the Los Angeles basin to San Francisco Bay. Such markets contain strong flows of business travel movement between regions of the urban area, and these markets have attracted conventional fixed-wing shuttle service. Ground access to major airports in this type of market is already very difficult, particularly during morning and afternoon peak periods, and is projected by the FAA to worsen and affect greater portions of the day. The airports in these corridors are congested and, in the case of LaGuardia, Kennedy, and Washington National, slot controlled. Because of the importance of these hub airports, inclement weather can reduce capacity by as much as 50%, sending a ripple of delay through the air system of the entire nation.

A tiltrotor system interconnecting the Boston–New York–Philadelphia–Washington, D.C. urban areas would require approximately 12 vertiports strategically located within high travel population centers. These vertiports would intercept travelers within a corridor close to their origin or destination. Operating in place of the existing shuttle system, the tiltrotor network could divert up to 15% of today's total passenger traffic away from airports and relieve 10% of the fixed-wing operations. Tiltrotor service in this market would provide an airborne form of intercity mass transit.

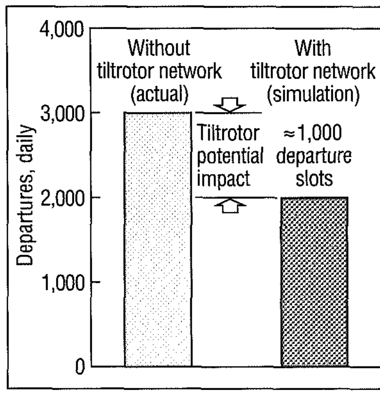
The "Spine" Network Service. The "spine" network would connect two or more city centers or high-density travel concentrations where an urban area-to-urban area tiltrotor market has not yet emerged. This point-to-point market is characterized by high origin and destination (O&D) traffic flows, demanding high-frequency service and short ground access times. As a result, it would tend to function independently of major airports. Minneapolis-St. Paul–Chicago–Detroit–Pittsburgh–Washington, Vancouver, B.C.–Seattle–Portland, and San Francisco–Sacramento are examples of potential spine markets.

High-Density Hub Feeder. A tiltrotor operating in the hub feeder market would connect small cities currently served by smaller turboprop airplanes with congested or slot-constrained hub airports. In this market, the tiltrotor could provide the operator a competitive edge by avoiding or reducing the pressure on existing slots, gates, and precision approach airspace. Further, extra hub airport capacity would be provided by the onsite vertiport. As much as 15% of a congested airport's operation could be diverted to a tiltrotor hub feed system.

In the Northeast Corridor, a combined urban area to urban area and hub feeder system, if available today, could make as many as 1,000 runway slots available each day. Such a combined network would:

- Relieve the high-density airport's airside congestion by reducing fixed-wing operations.
- Bypass airport ground congestion by flying point to point from local vertiports.
- Defer major capital investments in airport-related ground infrastructure (e.g., new tunnels, bridges, and access roads).
- Use existing airport assets more fully before building new ones.
- Improve service to the traveler by cutting portal-to-portal trip times by roughly an hour each way.

Effect of Tiltrotor on Fixed-Wing Operations—Northeast Corridor* (Sept. 1989 Conditions)



*Scheduled passenger service, Boston/New York/Washington, D.C./Philadelphia

Other Candidate Markets. Six candidate markets were judged to be unlikely candidates for initial tiltrotor service, for the reasons shown:

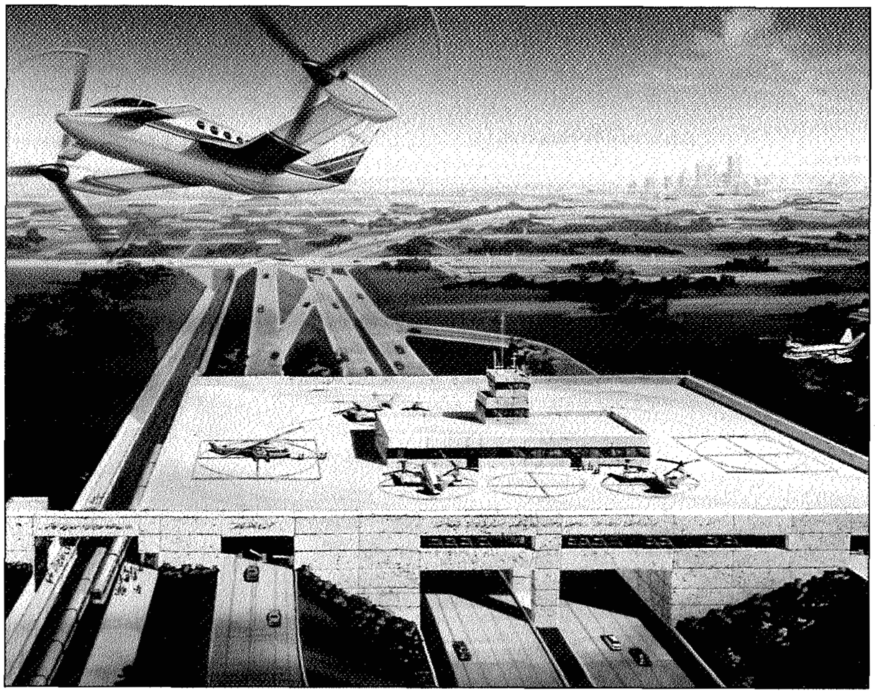
- Small city to small city: insufficient traffic.
- Small city to uncongested hub: questionable traffic and no forcing functions at the hub.
- Small city to major city center: insufficient traffic.
- Major city center to uncongested hub: no forcing function at the hub.
- Major city center-to-congested hub: Forcing function exists at the hub, but economics argue against the short hop between city center and airport. However, this service could evolve rapidly once a vertiport network is in place (e.g., Manhattan to JFK).

Vertiport Requirements

Study results indicate a successful tiltrotor system could include three types of vertiports:

- City center.
- Major airport.
- Full-service remote (high-density population center vertiports and intermodal vertiports with freeway access).

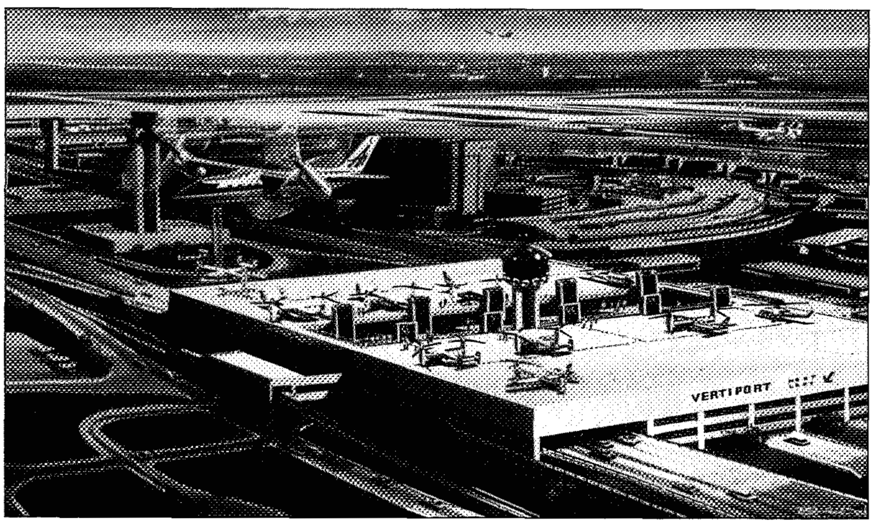
Artist's Conception: Intermodel Vertiport With Freeway and Rail Access



Ideally, vertiports will be sited at locations that are:

- In the center of density of the traveling population.
- Easily accessible by road and mass transit, requiring no more than 30 minutes access time during peak traffic hours.
- Preferred by passengers over airport locations.

Artist's Conception: Vertiport at Major Airport



Vertiports should be full-service, but especially so at remote locations. Services should include taxi stand, rental car facilities, drop-off capability, rail or bus connections, parking, and food services. Facilities should also exist for fueling and light maintenance, particularly for the full-service remote vertiport. Private auto parking facilities may not be justified for city center vertiports.

Meeting stringent noise levels is a prerequisite to approval of urban vertiport operations. Adequate area should be acquired to contain the obtrusive portion of the noise footprint within the vertiport.

A number of locale-specific vertiport feasibility studies are being conducted under FAA sponsorship. These studies are evaluating the market potential and economic feasibility of tiltrotor service and the prospects for locating vertiports in selected markets throughout the United States. Preliminary results of the studies are favorable; final results will be available later in the year. These studies should be examined for specifics outside the scope of this study.

Economics

Operating costs

The operating economics of a commercial aircraft consist of direct and indirect operating costs. Direct costs result from operating the aircraft. Included are cost of fuel consumed, flightcrew pay, airframe and engine maintenance (plus burden), hull insurance, and costs of ownership (depreciation and financing expenses, including spares).

Indirect costs are divided into three categories: aircraft-, passenger-, and cargo-related. Cargo-related costs are often excluded from commercial passenger analyses and are not included in this study.

CTR operating cost estimates were derived from and compared to operation of a commercial turboprop of the same seat count. There are two primary reasons for this:

- Validity of maintenance cost estimates. A turboprop and a CTR of the same size are similar in many overall aspects (size, number of turboprop engines, cabin furnishings, etc.) while differing in detail (landing gear complexity, number of control surface actuators, flap system complexity, engine power, etc.). Because of the overall similarity, the differences in detail could be closely examined.

- Economic relativity. Individual airlines show wide variation in operating cost performance, even when operating the same model of aircraft. There is no "standard operating cost" level. However, the economic relativity of two models of aircraft is nearly always similar, even when comparing results from airlines with widely varying cost performance; e.g., airplane A is always 10% more expensive than airplane B. For this reason, the normal industry practice is to focus on comparisons between models rather than on comparisons of absolute cost levels. In this case, the "price" of vertical flight should be more clearly reflected in side-by-side comparison with its most similar conventional counterpart; for this analysis, that counterpart is called the "equivalent turboprop."

Maintenance estimates

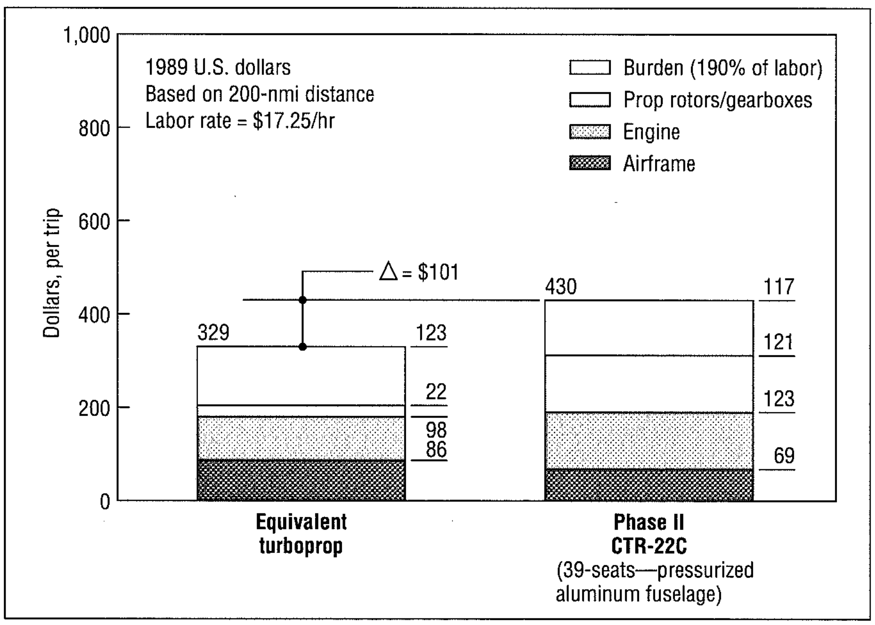
Lacking more definitive data, the Phase I study evaluated estimated CTR maintenance costs using figures derived from helicopter costs and V-22 Osprey estimates. These figures were then adjusted to an assumed civil environment where tiltrotors would spend an assumed 20% to 30% of their flighttime in a vertical flight mode. That assumption proved incorrect.

For Phase II, CTR maintenance cost estimates were derived from known costs for operation of a commercial turboprop of the same seat count. Adjustments were made to account for tiltrotor-unique systems and for commercial tiltrotor aircraft operating approximately 2% of their flighttime in the vertical flight mode (for a typical 200-nmi trip).

Total maintenance costs included airframe, engine, propeller/rotor, and overhead ("burden").

Overall, the study shows that maintenance costs for a tiltrotor in commercial service can be expected to be approximately 30% higher than those for a turboprop in the same service.

Estimated Maintenance Costs

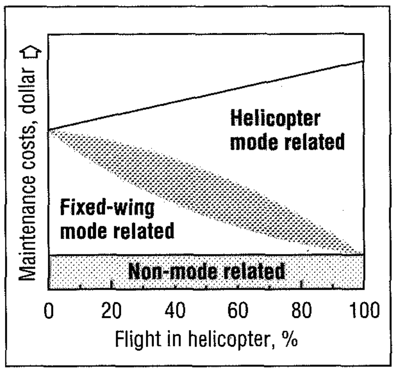


Comparing Phase I and Phase II estimates, some differences are worth noting:

- The rotor and gearbox maintenance costs determined by the Phase II study are about 33% lower than those from the Phase I study. Reducing the use of vertical flight mode systems from 20–30% to 2% significantly reduced maintenance costs.

- Flying in a commercial rather than military environment is anticipated to produce 50% fewer "induced failures" (failures caused by events and not design-controllable), further reducing maintenance material costs.
- Burden rates (overhead) used in the Phase I study were based on 50% of both material and labor costs; in the commercial aviation industry, burden typically is applied only to labor.

Effect of Helicopter Mode on Maintenance Costs



Cash operating costs

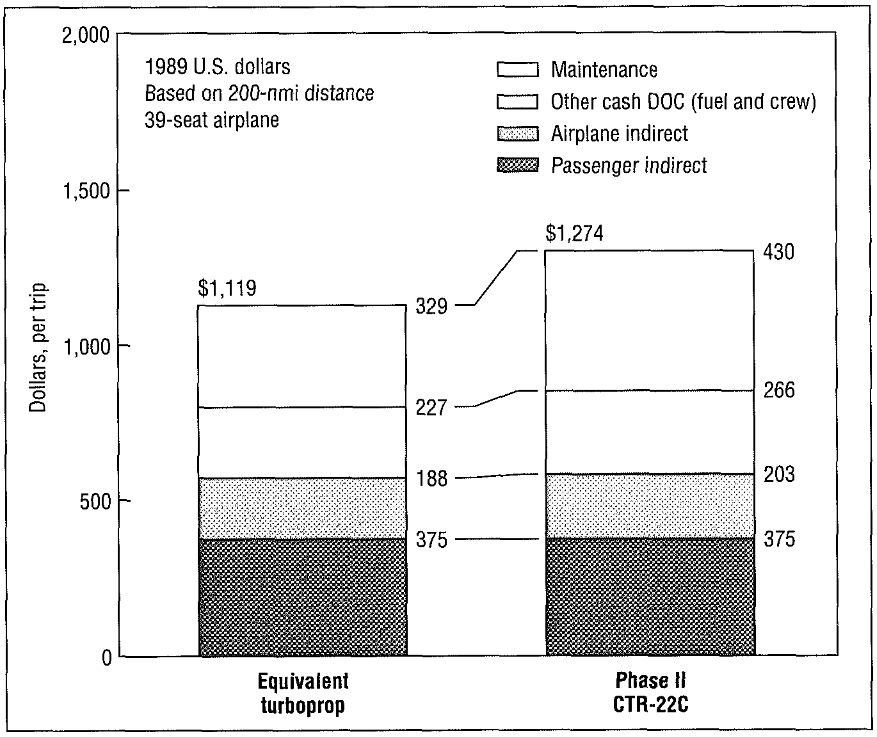
To estimate other cash operating costs, the commuter air carrier rules used in the Phase I study were updated from their 1986 cost basis to a 1989 cost basis. The update was based on operating cost changes reported to the U.S. Department of Transportation.

The figure below compares tiltrotor and equivalent turboprop operating costs; comparisons are based on total cash operating costs, which include the following elements:

- Cash direct operating costs (flightcrew, fuel, and maintenance).
- Airplane indirect operating costs.
- Passenger-related indirect operating costs.

Comparing a 39-seat equivalent turboprop with a tiltrotor (CTR-22C), the tiltrotor has 14% higher trip cash costs over a typical 200-nmi stage length; this equates to $6.10 higher cash cost per passenger at a representative load factor of 65%.

Total Cash Operating Cost



Cost to build

Military V-22 production cost experience has little direct comparability to manufacture of commercial tiltrotors. Manufacturing costs for military products like the V-22 tend to be higher than those for equivalent commercial products, for these reasons:

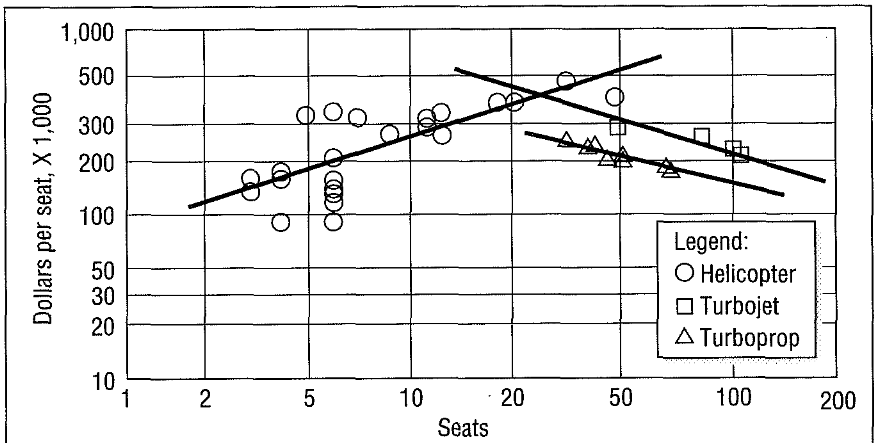
- Mission requirements. The V-22 was designed to meet the mission requirements of the Marines, Navy, Air Force, and Army. Meeting these multiple requirements appreciably increases fuel burn, adds structural weight, and adds complexity. Requirements for damage tolerance features, infrared suppressors, rear loading ramps, folding rotors, and other specific military mission equipment further increase the cost to build the V-22. A commercial product will be lighter, less complex, and more efficient.
- Material requirements. The V-22 uses composites extensively—for more than 50% of its structural makeup. The extent of composite use, the type of material used, and the construction methods employed were DOD directed in expectation of long-term exposure of the V-22 to a corrosive shipboard environment. A lighter, less complex, less expensive structure can be designed to meet civil corrosion requirments.
- Military procurement rules and regulations. U.S. Military procurement procedures involve lengthy, complicated, and costly processes to handle paperwork, inspection, accounting and documentation. Contracts require that manufacturers comply with these constraints, contributing to higher costs to build.
- Low production rates and program "stretchouts." Nothing influences unit production costs more dramatically than production quantity and changes in production rates. Higher production quantities and rates generate significant savings per unit.

Other NASA research (referenced in the Phase I study) indicates a tiltrotor's cost to build would be 1.4 to 1.45 times that of an equivalent turboprop. On that basis, the lowest CTR price could be expected to be approximately $300,000 per seat, or $12 million for a 40-seat CTR.

Selling price

Commercial aircraft are "market-based" priced. That is, their selling price is based on their value to the user. "Value" is established by how well the aircraft meets the buyer's operational requirements, compared to the competitive options available.

Selling Price



Source: Business and Commercial Aviation Planning and Purchasing Handbook, May 1990.

Market analysis summarized later in this report estimates the worth or value of a 40-seat CTR in the Northeast Corridor at $9.3 million more than an equivalent turboprop, assuming the tiltrotor operates in an off-airport, exclusive vertiport network. For that application, a selling price of approximately $17.3 million ($430 thousand per seat) is justified.

This study concludes that CTR selling prices for the independent network and airport feed market are likely to fall between $300,000 and $400,000 per seat, or $12 to $16 million for a 40-seat CTR.

System Operation

The goal of the analysis was fourfold:

- Assess the impact of a CTR system on commercial fixed-wing air traffic control and terminal operations.
- Estimate the potential air passenger diversion from fixed-wing to tiltrotor aircraft in an urban environment.
- Estimate the market-based economic "value" (i.e., purchase price) that a tiltrotor might command, based on competitive fixed-wing economic standards.
- Provide a case study calibration point for estimating worldwide commercial tiltrotor requirements.

Urban area to urban area market

This phase of the study concentrated on evaluating tiltrotor service as a replacement for conventional, fixed-wing, short-haul passenger service. The study postulated a Northeast Corridor system linking traffic centers in New York City, Boston, Philadelphia, and Washington, D.C.

Analysis proceeded in four steps:

- Forecasting passenger traffic.
- Scheduling tiltrotor flights to serve demand.
- Estimating market capture versus today's level of fixed-wing service.
- Determining the economic value of tiltrotor in this service.

The year 2000 passenger traffic forecast for city-pairs within this system was based on the DOT 10% sample and is summarized in the table below:

Passenger Traffic Forecast, Northeast Corridor

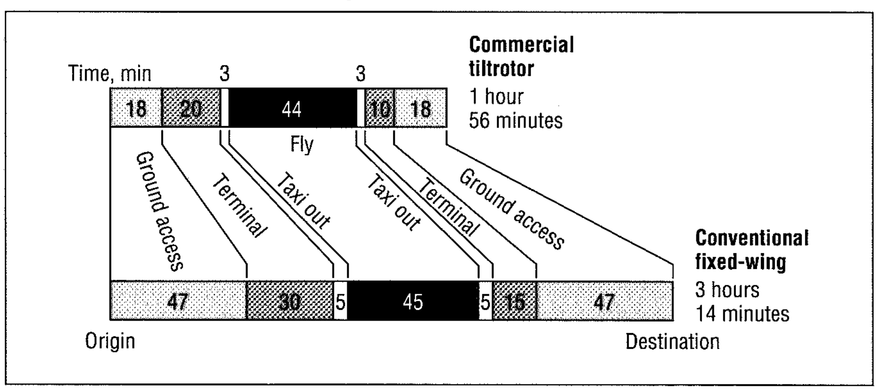
	Annual air passengers (X 1000)		
Market	1988	Growth (per year)	2000
BOS-NYC	3,203	6.0%	6,439
BOS-PHL	561	4.0%	902
BOS-WAS	1,048	6.9%	2,330
NYC-PHL	29	2.2%	38
NYC-WAS	2,932	4.3%	4,851
PHL-WAS	53	5.3%	98

Representative vertiport sites were selected for each city: six in New York City, three in Boston, two in Washington, D.C., and one in Philadelphia. Vertiport locations were based on Phase I work plus the market assessment surveys conducted as part of this study.

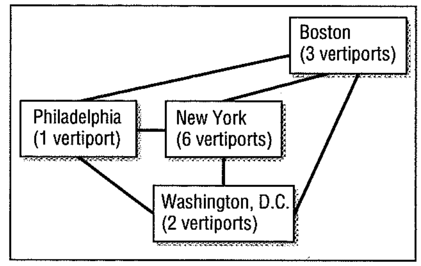
For this analysis, fixed-wing and tiltrotor total trip cost (including ground access cost) were required to be equal, thus having no effect on market capture. Using data obtained from the local port authorities, the traveler's ground travel time and ground access cost from domicile to closest airport or vertiport were determined.

To generalize the effect of frequency of service and time savings, schedules were built for a tiltrotor and competitive fixed-wing service with one to three competitors and 30- to 60-minute headway (i.e., frequency). These schedules were then evaluated using the *Boeing Market Share Model*, a proprietary system simulation model used for fleet planning. The analysis considered time savings and frequency of service in determining the portion of the demand a tiltrotor service would capture.

Northeast Corridor Tiltrotor Time Savings



Northeast Corridor Network



Representative Northeast Corridor Results (Year 2000 Demand)

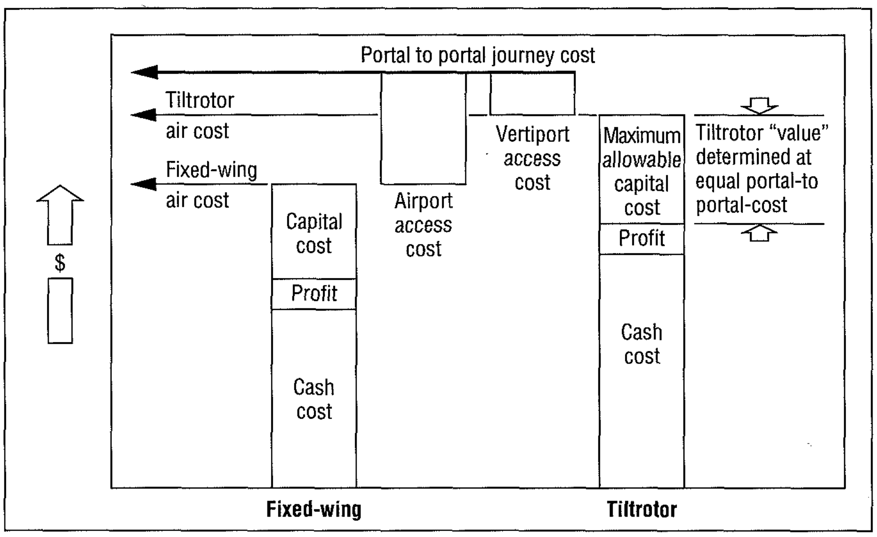
Tiltrotor capacity	40 seats
Average load factor	63%
Market capture	94%
Average segment	194 mi
Units required	164
Fleet daily trips	1,524
Average time saved, portal-to-portal (CTR versus fixed-wing):	1 hr, 18 min

To a potential operator, a tiltrotor's economic value in the urban market application can be found by solving for the purchase price that produces equal portal-to-portal cost between tiltrotor and fixed-wing aircraft; that is:

"value" = (competitor cost)—(tiltrotor cash cost + tiltrotor profit)

The following diagram displays this concept graphically.

Economic Value Determination

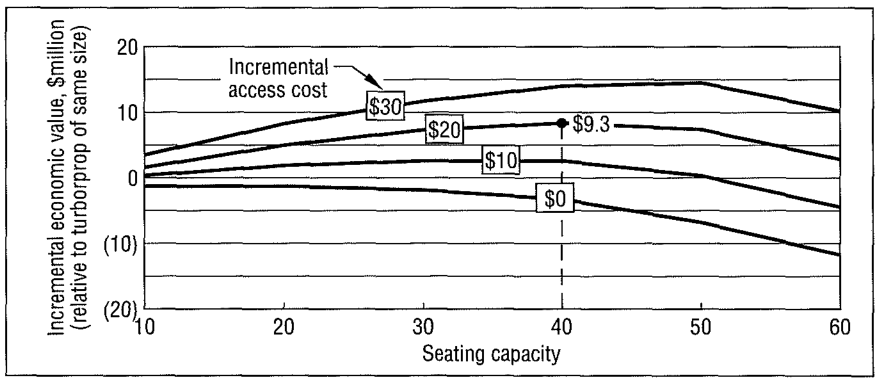


The year 2000 Northeast Corridor case study conditions produced an average incremental ground access cost per passenger for the CTR/vertiport system that is $20.30 less than that of conventional fixed-wing/airport operations. Assuming that incremental ground access cost could be included in the tiltrotor's airfare, a 40-seat CTR's "value" (i.e., the price that would produce an equal portal-to-portal cost) was estimated to be $9.3 million more than the cost of a turboprop of the same size.

Equal Portal To Portal Journey Cost to the Traveler:

Fixed-wing: $64.50 air portion plus $33.10 airport access =	$97.60
Tiltrotor: $84.80 air portion plus $12.80 vertiport access =	$97.60

Commercial Tiltrotor Economic Value



In keeping with the conservative analysis philosophy of Phase I, no credit was given to tiltrotor for the money value of the passenger time savings, and no diversion of traffic from ground modes was included in the demand projections. Clearly, if travelers assigned a value of only $10 to the 1-hour (approximate) portal-to-portal time savings and the reduced "hassle" associated with airports, the economic value of the tiltrotor is enhanced. Some shift away from rail and private auto also would occur where the tiltrotor offers shorter total trip times. If diversion from ground modes were appreciable, ground-level emissions and auto-related death and injury could be reduced.

High-density hub feed market

Hub feed operations perform a vital service, linking small town America to the national and global air system—but at a price. A significant share of the nation's hub capacity is consumed with small aircraft flying short hops; typically, 25% of the operations carry 10% or less of the total passengers. Diversion of a portion of these fixed-wing operations to a commercial tiltrotor network would increase airside capacity by allowing substitution of larger aircraft in the slots vacated by the small feeders, while maintaining the air service so essential to smaller cities. Every hub airport and hub/small city link faces unique market characteristics that would determine how much service would be offloaded to tiltrotors. A detailed examination of those characteristics was beyond the charter of this study.*

However, to provide perspective on the magnitude of the issues involved, the services feeding the northeast corridor hub airports were evaluated for conversion to tiltrotor service. A sensitivity analysis was performed on all markets (airports) less than 500 nmi from the major Boston, New York City, Philadelphia, and Washington, D.C. airports that were served with aircraft smaller than 100 seats in size. Assuming commercial tiltrotor service is substituted on an equal seat basis for the top one-half of those markets (i.e., for each hub airport, the top 50% feed locations ranked by turboprop seats per day), the following table shows the required annual value that would have to be placed on the now-available slot to produce economic indifference between turboprop and tiltrotor service (i.e., equal operating cost per passenger).

Slot Value Required

		Price range of 40-seat tiltrotor:		
	Slots* vacated	$12 million	–	$16 million
Boston	178	$14,000	–	$75,000
New York	281	$32,000	–	$121,000
Philadelphia	74	0	–	$65,000
Washington	74	$50,000	–	$170,000

*"Slot" defined as one takeoff plus one landing.

To put this analysis in perspective, a daily fee of $38 would offset a required slot value of $14,000. The mechanism by which slot value could be transferredbetween users was not addressed in this study.

* The next section of this report describes tiltrotor market opportunities. The objective of that analysis was to identify the "core" demand, which is in high-density urban area to urban area tiltrotor service. The hub feed market was excluded from that analysis.

Market Opportunity for Commercial Tiltrotor

Analyses conducted in Phase II of this study showed the potential opportunity for commercial tiltrotor urban passenger service to be large:

Civil Tiltrotor Opportunity, Projected by Major Region (40-Seat Tiltrotor)

	2000	2010
North America	1,270	2,404
Europe	615	1,152
Japan	500	861
Oceania	240	508
Total	2,625	4,925

The year 2000 opportunity represents a market valued between $32 billion and $42 billion, depending on the CTR's assumed selling price. Significantly, half of the identified market is in North America; consequently, the needs of the American marketplace will play a primary role in shaping the technical and market requirements of commercial tiltrotors.

When placed in perspective, the tiltrotor potential is seen as modest, compared to the worldwide commercial fixed-wing fleet, which now totals more than 12,000 aircraft in passenger service. Most forecasts show the fixed-wing fleet growing to 16,000 to 18,000 by the year 2000.

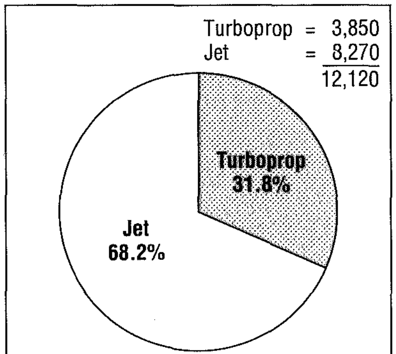
The fixed-wing fleet reflects the requirements of the marketplace in two ways that bear directly on the CTR market opportunity:

- A large proportion of the fixed-wing fleet is made up of small seating capacity turboprops (29 seats, average).
- Population tends to be centralized; as an example, 60% of the U.S. population resides within 1,000 miles of New York City.

As a result, the air transportation network is heavily oriented to the short haul, with high-frequency service provided by relatively small aircraft; worldwide, 76% of all scheduled departures are for destinations within 500 nmi.

The market opportunity analysis focused on these short-haul, high-density applications. Forecasts for 2000 and 2010 are compatible with Boeing Commercial Airplane Group's projections of expected traffic. The tiltrotor market identified is made up entirely of traffic that will be diverted from fixed-wing to tiltrotor aircraft. Diversion to and from ground systems was not considered.

Total World 1989 Year-End Fleet*
(Commercial Passenger Operations)

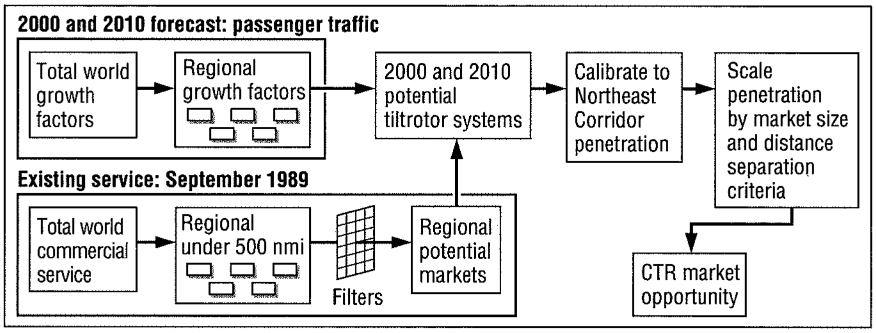


Source: Boeing and de Havilland Information

*Soviet Bloc excluded

Candidate high-density markets of 500 nmi or less were identified by geographical region from a database of scheduled services, as listed in the September 1989 Official Airline Guide (OAG) . This source was used because there is no worldwide data base for origin and destination (O&D) traffic. The thesis was that, with the application of proper screens to filter out flights that are incidental to the city-pair, the supply of available seats is a proxy for passenger demand.

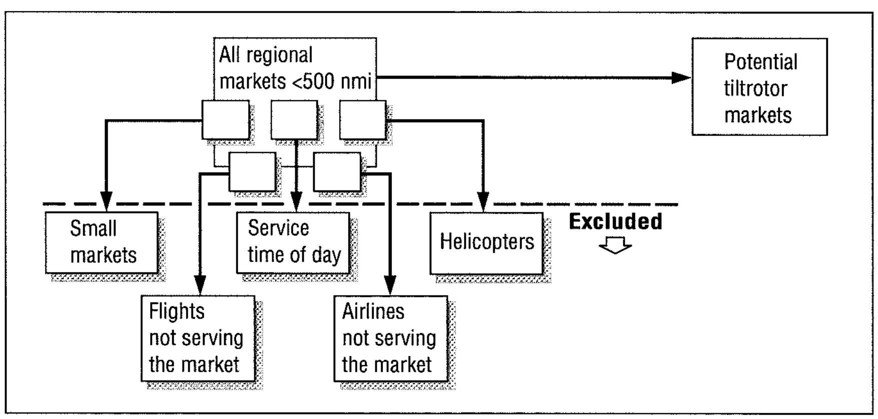
Market Opportunity Process: Total World Air Travel



The filters excluded:

- Small markets—service below 14 flights per week or less than 700 seats per week.
- Service time—departures between 8:00 p.m. and 6:00 a.m.
- Helicopters—all helicopter service.
- Nonserving airlines—airlines providing fewer than four flights per week.
- Nonserving flights—flights where the longest leg in the itinerary exceeded 1,000 nmi.

Market Filters

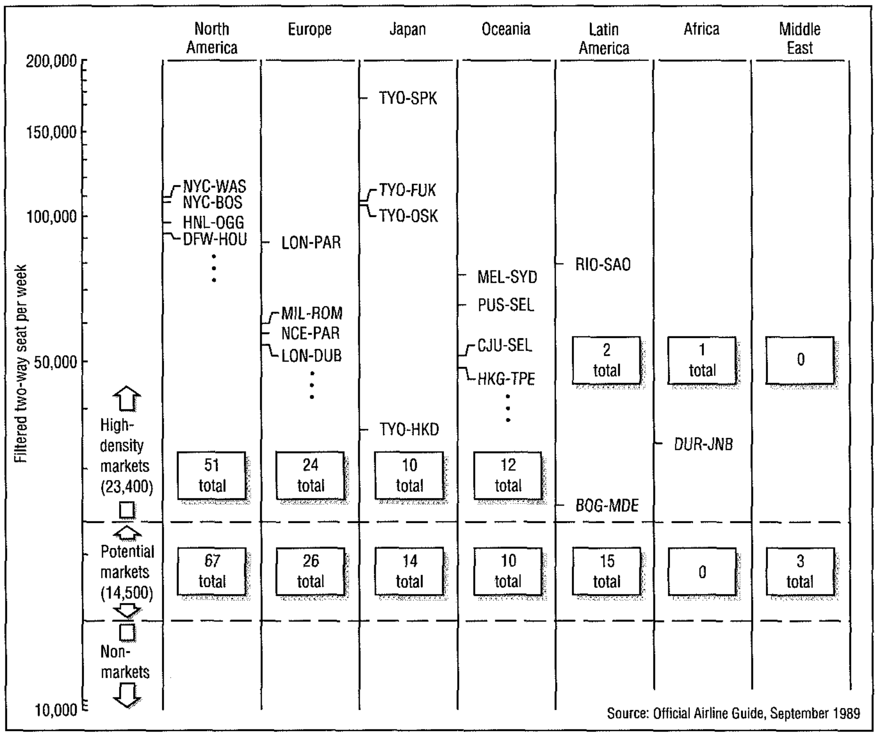


The resulting potential markets were ranked by density (seats per week after filters were applied). Further analysis was limited to examining only those markets generating at least 14,500 seats per week (equal to the 50th densest European market). Two considerations led to this somewhat arbitrary cutoff point:

- Smaller markets tend to be sensitive to local conditions and are therefore more complex to evaluate without local knowledge.
- The objective of the market demand analysis was to identify the magnitude and geographic location of the high-confidence CTR core demand. Including lower confidence applications would tend to dilute the credibility of the results.

This ground rule effectively eliminated Latin America, Africa, and the Middle East as tiltrotor market regions and also excluded what had previously been identified in the market assessment portion of the study as a strong potential market: high-density airport feed from smaller cities. The study team recognized that this arbitrary decision would understate the full CTR potential.

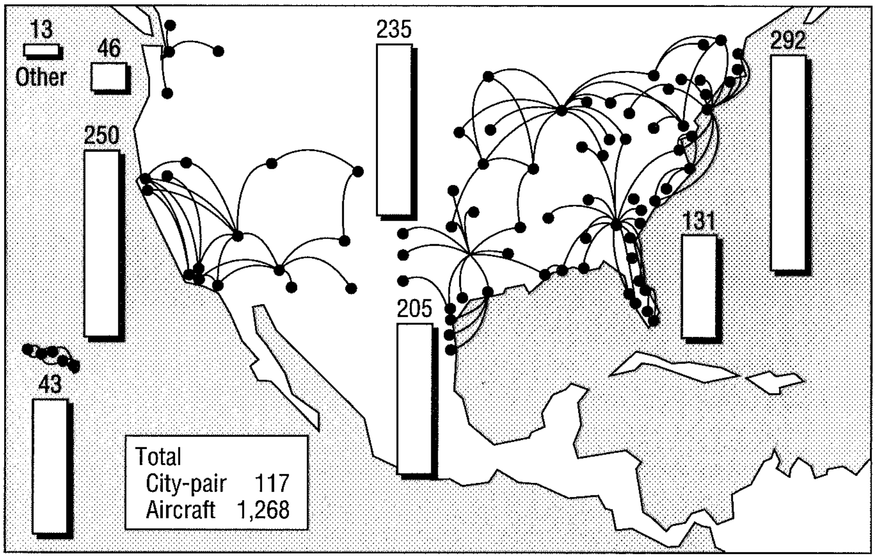
Potential Tiltrotor City-Pairs



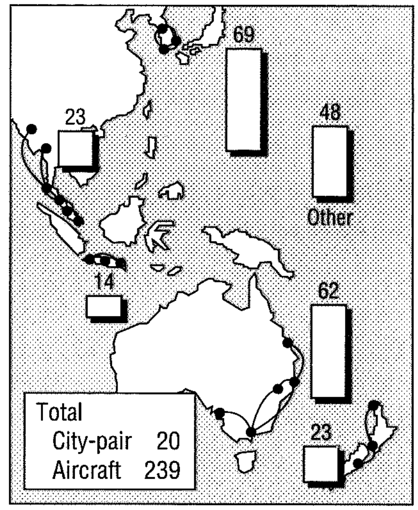
Source: Official Airline Guide, September 1989

The tiltrotor market share and number of aircraft required for each market (city-pair) was generalized from the system analysis performed for the Northeast Corridor. Adjustments were made for market density (size) and city-pair distance (CTR portal-to-portal elapsed time advantage). Where the resulting number of units required to service the area was less than five, the market was judged to lack sufficient "critical mass" to be functionally viable; in such cases, units and markets were not counted.

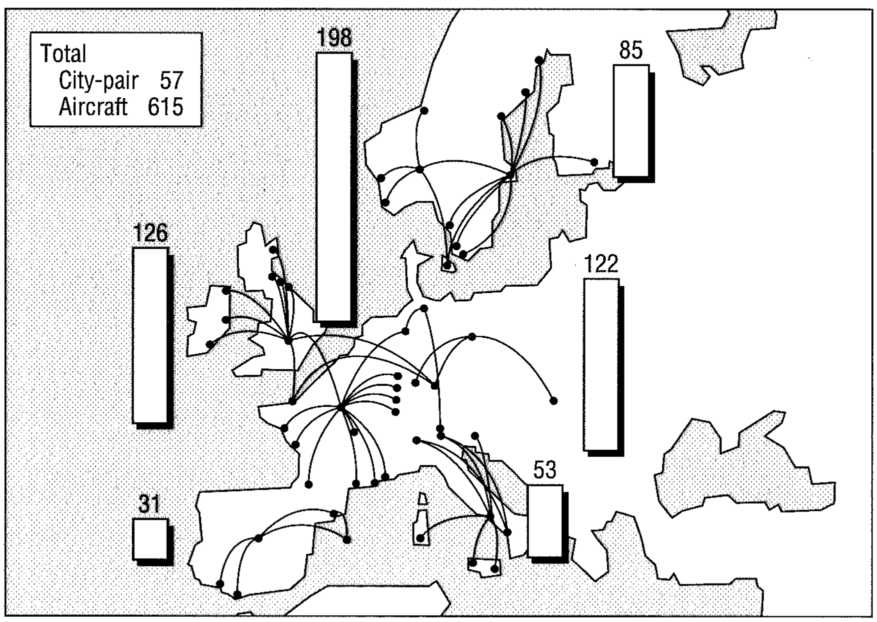
North America: CTR Projected System in Year 2000 (Passenger)



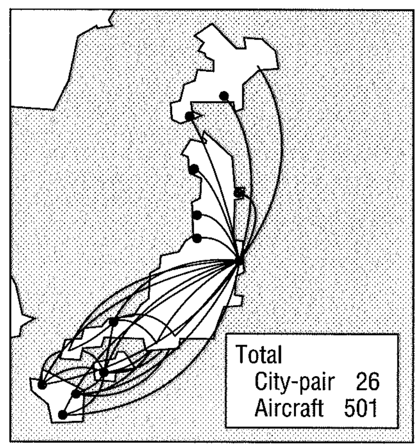
Oceania: CTR Projected System in Year 2000 (Passenger)



Europe: CTR Projected System in Year 2000 (Passenger)



Japan: CTR Projected System in Year 2000 (Passenger)



TASK II: COMMERCIAL STANDARDS AND TECHNOLOGY BENEFITS

This task (1) explored the current V-22 design to see where commercial design standards could be applied and (2) examined technology areas to see what further benefits could be applied to the design of a commercial tiltrotor.

Three sets of criteria drove the analysis:

1. FAA certification. The commercial tiltrotor must meet Interim Airworthiness Criteria (IAC) for Powered Lift Transport Category Aircraft (FAA, DOT July 1988).
2. Product-driven criteria. A V-22-based commercial tiltrotor can realize significant savings in weight and cost by eliminating military mission and survivability features.
3. Market-driven criteria. Both operators and passengers must accept the tiltrotor. Operators want reliability, flexibility, and profitability; initial cost, support systems commonalty, spares interchangeability, reliability, maintainability, and maintenance costs are all important. Passengers' prime concerns are safety, comfort, convenience, and value.

Benefits of Applying Commercial Standards

Changes for commercial operation were divided into two categories. The first category included those primary changes that are essential to convert the V-22 into a civil transport. Uprate of the drive system for increased takeoff weight was included in this category. The second category included enhancement changes that are optional but strongly recommended because of benefits attributable to the change. Eliminating wing stow and rotor fold, redesigning the fuel system, and using commercially common and structurally compatible composite materials were examples. The cost to design and develop these optional changes approaches $110 million, but benefits include an overall weight reduction of 1,745 lb and a manufacturing cost reduction of approximately $4.15 million per aircraft.

Weight Statement: Minimum Change Commercial Tiltrotor

Transmission Uprate
Redesign of the drive system would upgrade the one engine inoperative (OEI) rating to 8,072 shaft horsepower (essentially the same as Phase I's CTR-22B).

Avionics
Most V-22 Mil-SPEC avionics would be replaced with equivalent commercial units.

Flight Control System
No redesign of the V-22 redundant digital fly-by-wire flight control system is anticipated.

Flight Deck Controls and Displays
Achieve commonality with commercial cockpit systems, certification standards, commercial carrier preferences, and ongoing development.

Passenger Cabin (add):
- Emergency provisions
- Safety equipment
- Noise treatment
- Windows, galley, and lavatory
- Heating and cooling systems.

Change	Weight change, lb
Primary Changes	
Transmission uprate	372
Avionics	-630
Flight control software (if needed)	0
APU firewall	20
Exterior noise certification	0
Landing gear	7
Cabin noise treatment (85 dBA)	500
Cockpit	-65
Cabin accomodations	1,162
Cargo and utility	-653
Total (primary changes)	713
Enhancement Changes	
Alternate composites	-200
Wing-stow elimination	-744
Blade-fold elimination (total)	-929
Wing-tank fuel system	-168
Sponson fuel system	-417
Total (enhancements)	-2,458
Grand Total:	**-1,745**

Fuselage Configuration
Eliminating the load ramp and military requirements for battlefield survival.

Materials
Improved "toughened" carbon-epoxy composites are now available.

Wing and Rotor Assembly
Eliminating the V-22 wing-stow feature reduces aircraft weight by 744 lb. Eliminating the V-22 folding blade system saves an additional 929 lb. Both changes also improve drag, operating economics, reliability, maintainability, and maintenance cost.

Fuel System
Changes to the military fuel system are substantial, because a commercial tiltrotor does not need to meet military ballistics tolerance requirements. Wing tank fuel capacity is increased by 32%.

Changes Explored

Avionics

V-22 military specifications avionics would be replaced with commercial units to provide commercial tiltrotor pilots with familiar avionics:

- An integrated display system, including primary flight display, navigation display, and engine-indicating and crew-alerting system.
- A flight management system.
- Inertial reference and global positioning systems.

Besides the weight and cost savings associated with commercial avionics, their use would also reduce pilot training costs, because pilots would be familiar with the avionics suite.

Flight control system

Significant redesign of the V-22 redundant digital fly-by-wire flight control system is not anticipated. However, the Interim Airworthiness Criteria (IAC) does not address fly-by-wire systems in great depth; the manufacturer and the FAA will need to continue to work together to ensue that appropriate standards for a commercial tiltrotor are established.

Electrical and hydraulic systems

Electrical system. Changes to the electrical system depend on whether a V-22 derivative or an all-new commercial tiltrotor is built. Power generation in a V-22 derivative would be identical to the V-22; an all-new design would use lower cost, lighter weight commercial equipment. Lighting would undergo change in any event to eliminate unneeded military requirements and to meet IAC requirements for commercial aircraft. Overall, these changes will add slightly to the weight of the aircraft, but cost changes tend to be offsetting. Commercial-level lightning-protection standards will need to be addressed. The V-22 structure is protected by the expanded copper foil within the composite skin panels, and it is difficult to electrically bond the foil to the external lights. As with the V-22, a minimum-change commercial tiltrotor would use lightning-protection devices to guard critical equipment in the cockpit.

Hydraulic system. Applying commercial standards and eliminating two unique military requirements (ballistically tolerant swashplate actuators and wing-stow hydraulics) create large savings in cost and weight. Less major changes to V-22 hydraulics may be necessary to: (1) provide fluid quantity indicators at a crewmember station, (2) install shrouds around lines or reroute lines in the passenger cabin, (3) provide dual rather than single left and right brake systems, (4) incorporate jam-proof valves in control actuators, and (5) incorporate swashplate/actuator motion-limiting stops. Trade studies are recommended to assess the use of commercial grade fluids and support equipment. Most commercial hydraulic carts, for example, are of the 3,000 lb/in^2 and 10 gal/min variety; the V-22 requires 5,000 lb/in^2 and 15 gal/min delivery for full system checkout. The V-22 complies with military standards for flammable fluid fire protection that exceed the requirements of the IAC.

Flight deck controls and displays

For a commercial tiltrotor, redesign of V-22 controls and displays is needed to achieve commonality with commercial cockpit systems. Redesign is driven by certification standards, commercial carrier preferences, and ongoing development of an industry standard for cockpit configuration.

Current V-22 display units are cathode ray tubes (CRT). However, it is quite likely that lightweight, liquid-crystal, flat-panel color displays will be a practical standard for civil transport. These displays will use less power and will occupy less depth than the V-22 CRTs.

A potential obstacle in the transition of tiltrotor technology into an accepted commercial passenger transport product is the pilot-machine interface. Tiltrotor has evolved from a helicopter background; initial production is for a military customer, and the aircraft has been developed by helicopter companies. All of these factors influenced the relationship of pilot control of the machine as it exists today. The helicopter pilot in command is traditionally seated in the right seat, a collective lever is used to control engine power, and a stick is used for lateral and pitch control. Helicopter controls are appropriate for a machine thought of as a helicopter, with a large portion of its flight spectrum in hover and with pilots flying only similar vehicles. However, commercial tiltrotor may have none of these characteristics, and the question of "what is the safest, most natural way for the commercial pilots who will be flying CTR to interface with the aircraft?" must be addressed.

From a commercial perspective, these are the issues:

Pilot-in-command position. In fixed-wing aircraft, the pilot in command traditionally sits in the left seat. Actual operation of the aircraft is accomplished by either the left or right pilot.

Collective versus throttle. For fixed-wing service, throttles are center-mounted pedestal throttles that are accessible by either pilot (some procedures require simultaneous throttle manipulation by both pilots). The throttle is moved forward for more power. Engine power is controlled in a helicopter with individual collective levers located to the left of each pilot's seat. The collective is moved up for more power.

Pilot community. Nearly all commercial passenger-transport pilots belong to a union/trade organization. Promotion opportunities occur strictly by seniority for those who meet the necessary proficiency standards. Pay is determined by aircraft productivity (size and speed) and pilot position (captain or first officer). In airlines with several equipment types, pilots move frequently between positions. The typical career path is from first officer on the smallest aircraft type through all first officer positions on progressively larger aircraft, then back to the smallest type as a captain and finally progressing to command of the larger types. This continual movement between aircraft mandates a high degree of cockpit standardization in an airline's fleet, for safety as well as training efficiency.

The commercial tiltrotor typically will spend approximately two minutes of each flight in the vertical flight mode. However, those are the minutes of flight during which safety is most critical. For this new class of commercial aircraft, the most natural interaction between pilot and aircraft (the man-machine interface) must be researched and appropriate control devices developed. Such research cannot be done in isolation from the pilot community. If tiltrotor functions as "just another airplane," pilots will be primarily fixed-wing people transitioning through the tiltrotor. If tiltrotor operation is isolated from airline-type procedures, the pilot pool may be more stable. To some extent, the opposite may also be true: the CTR's flight deck may determine its commercial acceptance.

Materials

Improved "toughened" carbon-epoxy composites are now available; they can improve reliability and maintainability and reduce the weight of a V-22-based commercial tiltrotor by 200 lb. For market acceptability, an all-new commercial tiltrotor would probably employ a traditional metal fuselage that would weigh more than a composite-skinned commercial version of the V-22. However, the weight penalty would be more than offset by the improved aerodynamics and lower production costs of the all-new metal fuselage design.

Fuel system

Changes to the military fuel system are substantial because a commercial tiltrotor does not need to meet military ballistics tolerance requirements. Wing tank fuel capacity is increased by 32%. Total weight savings is 585 lb, allowing improved CTR capacity and/or range.

Wing and rotor assembly

Eliminating the V-22 wing-stow feature reduces aircraft weight by 744 lb. Eliminating the V-22 folding blade system saves an additional 929 lb. Both changes also improve drag, operating economics, reliability, maintainability, and maintenance cost. Other design improvements (e.g., designing metal parts for no yield at load limits, adjusting design criteria of infinite fatigue life, reducing design angular velocity rates to commercial standards) save additional weight and cost without penalizing reliability or maintainability.

Fuselage configuration and ramp

Numerous changes are proposed to the V-22 fuselage to convert it to a commercial tiltrotor. Eliminating the loading ramp and military requirements for battlefield survivability, in particular, reduces the weight and cost of the commercial tiltrotor. These weight and cost savings are offset, however, by more stringent commercial requirements in other areas:

- Landing gear lateral loads.
- Emergency provisions (ditching, emergency evacuation, flotation volumes, egress window jettisoning).
- Safety equipment.
- Passenger cabin noise treatment.
- Passenger cabin windows, galley, and lavatory.
- Passenger cabin heating and cooling system.

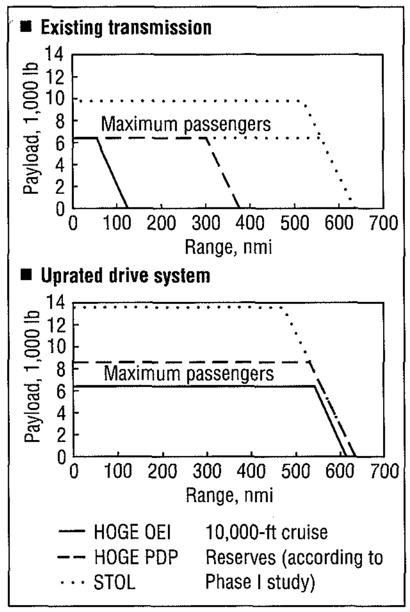
Transmission uprate

The commercial tiltrotor discussed here is similar to the minimum change CTR-22A discussed in phase I of this study. Compared to the CTR-22A, the minimum-change tiltrotor that results from applying commercial standards is significantly lighter.

For commercial one engine inoperative (OEI) operations, an uprated drive system is recommended and would incorporate a significant (on the order of 20%) increase in power rating for several drive system components. This significant redesign of the drive system would upgrade the rating to 8072 shaft horsepower (shp) (essentially the same as the phase I CTR-22B). Weights would increase by 372 lb with this change, but range capability would increase dramatically. In addition, the maximum payload limits would increase. However, these payloads generally exceed the full-passenger load requirements and are of little utility for a passenger-carrying vehicle.

- 45,120 lb, HOGE, OEI (hover out of ground effect, one engine inoperative).
- 47,380 lb, HOGE, PDP (performance deficiency parameter).
- 52,300 lb, short takeoff and landing (STOL).

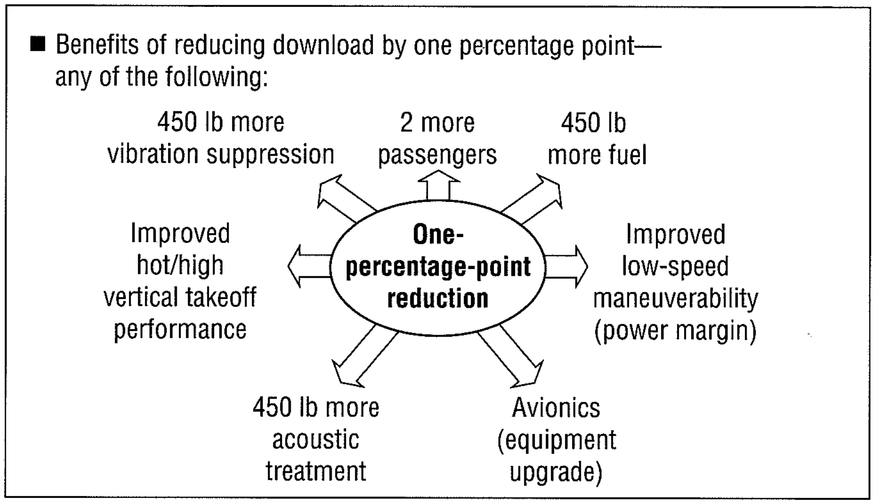
Payload Range



Download reduction

Download is the downward force on wings and fuselage created by the rotor wake in the vertical flight mode; the more download, the less thrust available for lifting the airplane. Download is expressed as a percentage of rotor thrust. Download on the V-22 is in the 9% range. Reducing download of the V-22 by a single percentage point (9% to 8%, for example) increases its useful load capacity by 450 lb. Applied to power requirements only, this 450-lb download reduction would reduce power requirements by 116 hp.

Download Reduction



Proven methods to achieve reduced download on a V-22-based commercial tiltrotor are (1) using increased flaperon deflection, (2) using flaperon seals as spoilers, and (3) using rotor symmetric lateral flapping. Together, these can produce a 3.1% increase in maximum takeoff weight, allowing an 18% increase in payload limit or a 26% increase in range.

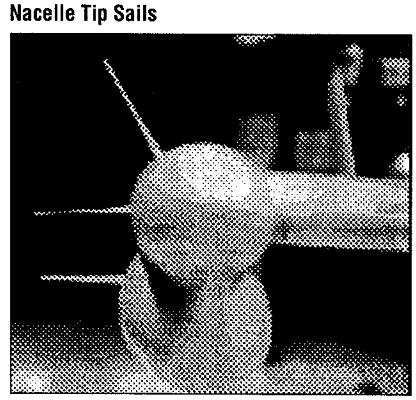
Drag reduction

Drag on a V-22-based tiltrotor may be reduced in a number of ways:

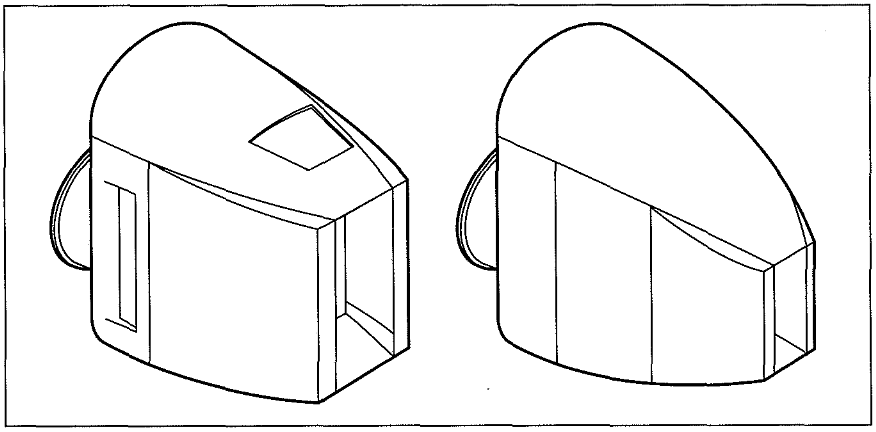
- Adding tip sails to nacelles.
- Revising spinner geometry.
- Changing to conventional tail.
- Removing protuberances (military antennas, etc.).
- Removing or modifying engine infrared suppressors.

Applied to a V-22-based commercial tiltrotor, these changes could reduce drag by 27%, which would increase range by 18%.

Nacelle Tip Sails



Remove IRS and Modify Nacelle/Exhaust To Reduce Drag



Additional drag reduction can be obtained by removing wing folding, lowering the wing-fuselage interface, and optimizing fairings. This modification has a primary benefit of saving weight, but the drag reduction that would also result would yield a 4% increase in range or a 9-kn increase in speed. The 744-lb weight reduction, in itself, increases range by 1%. Alternately, if 744 lb of fuel were added, range increases by 13%. Major redesign of the wing-fuselage interface structure would be required to realize these drag reduction benefits, however.

Performance Improvements, Compared With CTR-22B

	Range, nmi	Weight, lb
Download	+147	+120
Drag reduction	+106	-4*
Engine uprate	+33	0
Wing and fuselage modification	+30	*
Total	**+316**	**+116**

*Note: Includes sails, empennage change, and engine exhaust modification. Weight changes associated with wing and fuselage modification and with removal of military antennas and associated systems are accounted for in earlier summary.

New fuselage

Changing to a circular fuselage with a tapered afterbody (from the V-22 rounded boxcar shape, with rear ramp) is a major design change, although not particularly challenging from a technical standpoint. In addition to creating space for 39 passengers (compared wtih 31 for the V-22 type fuselage), the reduced drag of a circular fuselage would produce these alternative benefits:

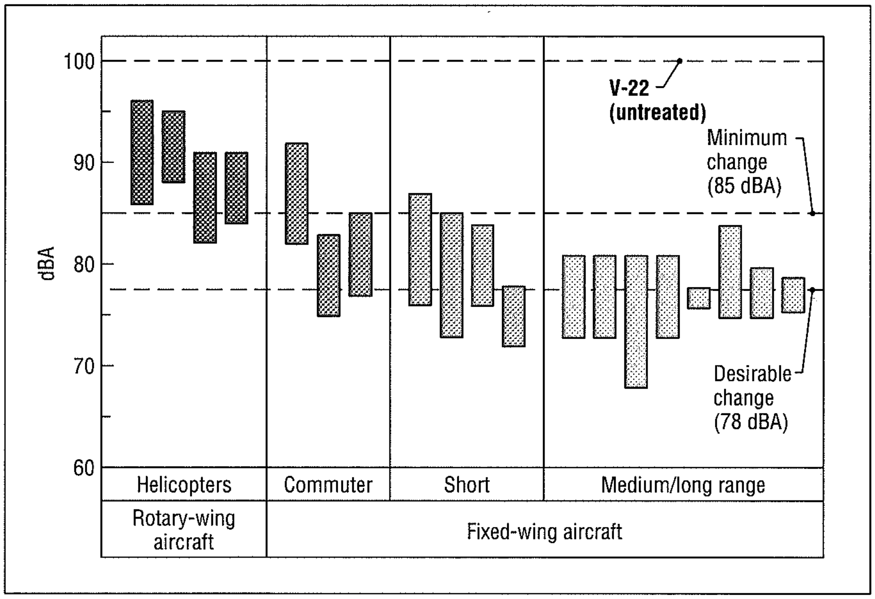
- 399 lb less fuel needed for 600-nmi range.
- 8% increase in range with full fuel load.

Constructed of aluminum, with seats for eight additional passengers, the fuselage would weigh 203 lb more than the V-22 fuselage. If constructed of new resin composites, the circular fuselage would weigh 372 lb less than the V-22 fuselage. Market acceptance (risk) argues strongly that a near-term commercial tiltrotor would have a pressurized aluminum fuselage.

Noise (internal)

The interior noise level of modern commercial short-haul passenger planes is in the 75- to 85-dBa area. The CTR-22B assumes an 85-dB internal noise standard, achieved by using 500 lb of active suppression devices and passive insulation materials (plus trim and furnishings). To meet the 78-dB level of quietness, 720 lb of similar treatment would be required. If only passive methods were used, 1,350 lb of insulation material would be needed to achieve the 78-dB goal. Aggressive development and validation of active suppression systems for civil tiltrotors is therefore worthwhile.

Cabin Noise Level Ranges for Current Aircraft Types



Noise frequencies in the V-22 are two octaves lower than those inside most turboprops. Experimental validation of the appropriateness of the 78 dB interior noise level is needed.

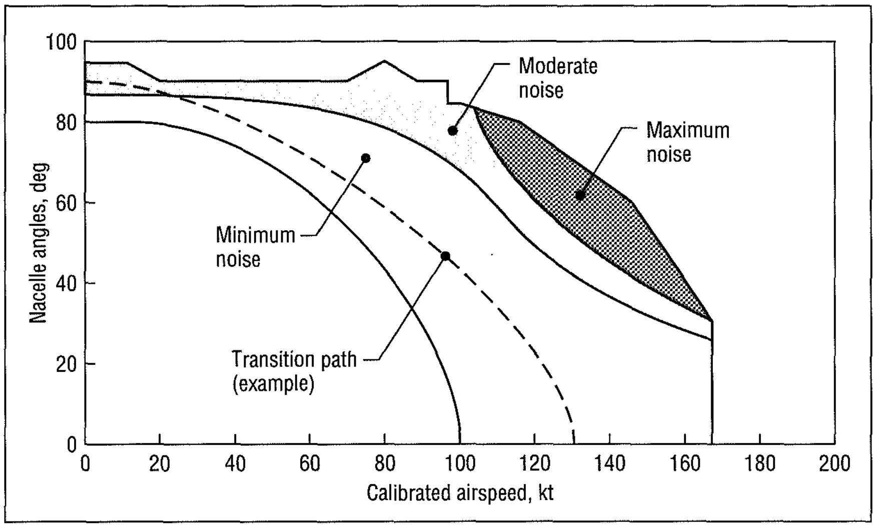
One method of reducing accoustical insulation requirements is to increase the clearance between the rotor tip and the fuselage by increasing wing span. Moving the rotor tip an extra 12 in away from the fuselage reduces interior noise by 4 dB, but requires a heavier, longer, stiffer wing. A careful trade study of rotor tip-fuselage separation will be required during preliminary design of new commercial tiltrotor configurations.

Noise (external)

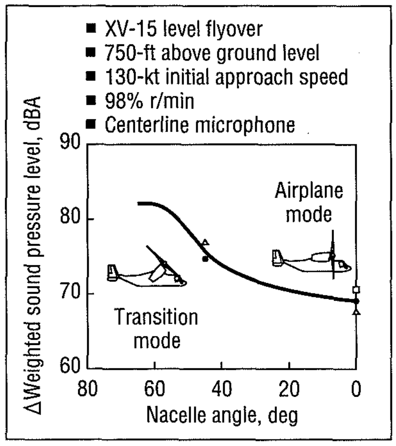
Environmental noise is probably the most sensitive issue to potential vertiport neighbors, and this issue will need to be addressed in certification standards, vertiport design standards, terminal area operations, and noise-abatement procedures. The question of noise reduction at its source also needs to be addressed, and technology needs to be developed to minimize noise generated by the rotors. A combination of noise reduction technology and noise abatement approach procedures can produce a commercial tiltrotor that is compatible with stringent community noise standards.

Such work is now under way. Bell Helicopter Textron, Inc., under contract to NASA-Langley, is now generating noise contours ("footprints") for XV-15 takeoffs and approaches.

Noise Sensitive Regions of XV-15 Conversion Corridor



Noise Level Versus Nacelle Angle During Transition and Airplane Mode for the XV-15



The tiltrotor is much quieter in the cruise mode than in the vertical flight mode. Conversion between modes needs to be done to minimize noise while maintaining the best safety, pilot load, and passenger comfort levels. The "minimum noise" profile of the XV-15 flight envelope above is especially interesting because the combinations of nacelle angle and forward speed that minimize external noise also are favored by pilots for reasons of safety, pilot load, and passenger comfort (additional discussion under Operations Analysis). V-22 data are needed to validate noise profiles for larger commercial tiltrotors.

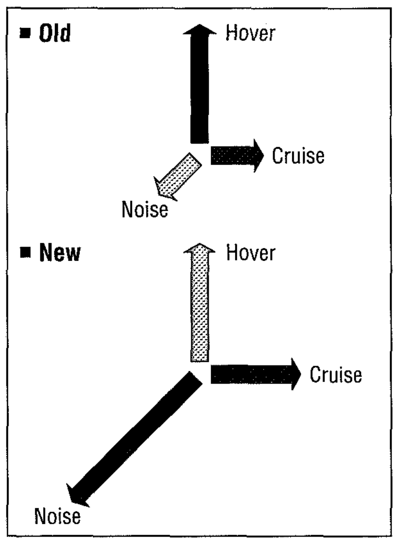
Long-Term Technology Improvements

All areas of tiltrotor technology will benefit from additional research and development, but high priority should be placed on technologies and operational procedures that reduce noise.

Noise

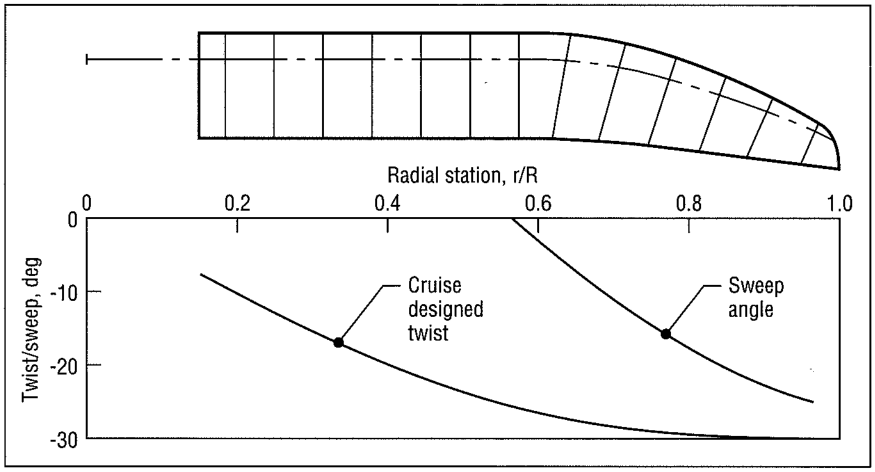
Operational techniques may significantly abate noise perceived in the vicinity of vertiports; these need to be optimized by flight test experimentation and simulation studies linked with noise analyses. These operations studies should also be supplemented by development of airfoil and rotor blade designs that reduce noise at the source.

The New Paradigm in Proprotor Design



Experiments have shown that an elliptical tip can reduce far-field noise by as much as 5 dB. Adding sweep to the tip and using thinner airfoils can also reduce noise. Reducing noise at the source would benefit interior noise levels and produce corresponding weight savings in insulation and wing structure. These "at the source" noise reductions warrant much more study; a program of design, scale-model testing, large-scale testing, and flight testing is recommended.

Advanced Geometry High-Speed Rotor Blade



Performance improvements

Maximize chord of flap relative to wing chord and use the interconnecting drive shaft as a rotating cylinder to energize the flow from the wing to the flap. These refinements could yield a 2% reduction in net download, which would translate to payload increase of about 900 lb.

Drag improvement. At speeds now seen for the CTR, modest further improvement in drag is foreseen from technology improvement, beyond those described previously. At higher speeds (over 400 kn), a thinner wing designed to the speed requirement is worthy of consideration. Wing twist to optimize the rotor wake interactions with wing flow would also produce benefits.

Rotor Technologies. A quiet, efficient rotor system is of paramount importance to a successful commercial tiltrotor. Promising areas of further study include—

- Aerodynamics. Optimizing the blade tip shape, blade twist, planform, and section will improve efficiency and reduce blade vortex intersection noise.
- Rotor design. Rotors with four or more blades can reduce noise and rotor vibration forces, with minimal weight penalty over current 3-blade systems.
- Hub design. Gimbaled hubs in use on first-generation tiltrotors are proven and reliable. Further research on soft-in-plane hingeless rotors may demonstrate advantages in vibration, reliability, and maintenance.

Advanced engine technologies. Both proprietary and government-sponsored research is developing advanced rotorcraft engines. The Integrated High Performance Turbine Engine Technology initiative will apply NASA, DOD, and industry resources to these efforts, which will double propulsion system capability by the year 2000. Improved engines also will use less fuel and require less maintenance. Integrating improved engines into the commercial tiltrotor would increase payload and range, reduce operating costs, and make it easier for the civil tiltrotor to meet engine-out certification standards. Optimizing emergency power ratings so that engine life would be unaffected may be extremely beneficial to maintenance cost.

Using more than two engines. Another way to increase tiltrotor performance is to add engines. CTR configurations employing three and four engines were explored in this study. The cost-effectiveness of this approach appears less promising than employing higher performance engines (the trend throughout aviation).

TASK IV: OPERATIONS ANALYSIS—APPROACH AND LANDING PROFILES

Operations analyses were conducted to evaluate the CTR airplane on approach and landing. The objectives were to:

- Assess CTR airplane capabilities.
- Recommend safe flightpath procedures that, with expanded study, will lead to FAA terminal instrument procedures (TERPS) for the commercial tiltrotor airplane.

Operations analysis proceeded under the assumption that CTR airplanes will operate from dedicated vertiports in or near urban areas. Such operations may require steep approach and departure paths, which may also reduce the size of the noise footprint and duration of noise beyond the confines of the vertiports, resulting in less community noise disturbance.

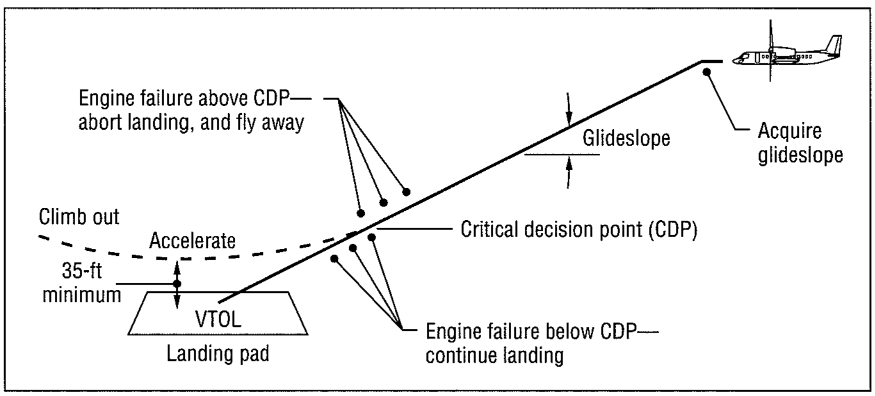
Simulations

The CTR-22C airplane configuration was presumed for this study, which enabled use of the V-22 flight simulator to produce thorough, reliable information while saving significant time and effort.

Six pilots from NASA, the FAA, Boeing Helicopters, Bell Helicopter, Textron, Inc., and Boeing Commercial Airplane Group flew seven instrument landing profiles (seven different glideslopes) on the V-22 flight simulator. The profiles were simulated with flight director position data and unprocessed microwave landing system (MLS) position data.

Simulations terminated in either an all-engine-operating landing or a simulated engine failure (with either a one-engine-inoperative landing or an aborted landing and climbout).

Landing Profiles

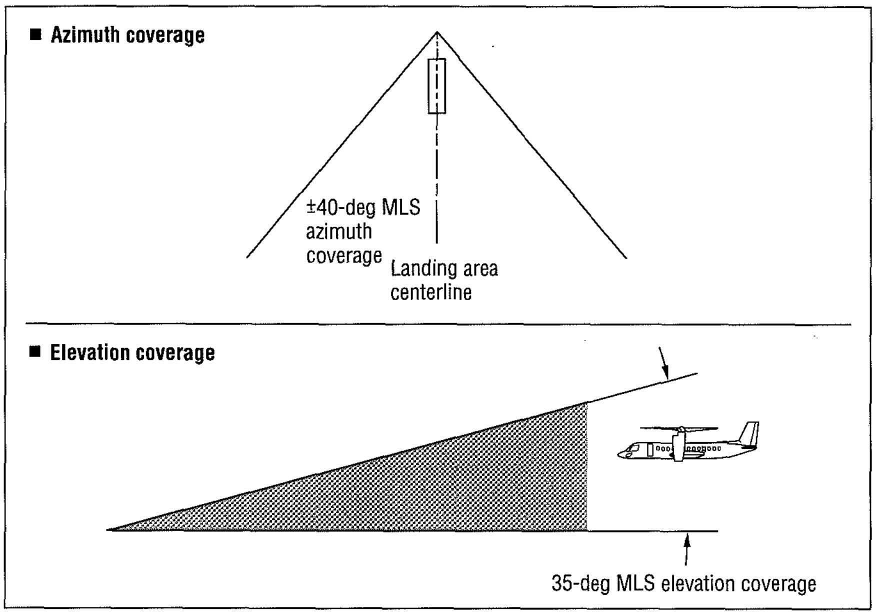


V-22 Simulator Cockpit. The V-22 simulator has dual side-by-side seats and a programmable force-feel system. Instrument information was presented through the simulator's multifunction displays. High-resolution, out-of-window visual imagery covered a large field of vision (140 deg horizontally, 60 deg vertically).

The computer image generator produced visual scenes that provided pilots with navigation landmarks and geography for the Long Island Sound area, Rhode Island, New Jersey, most of Connecticut, and parts of Pennsylvania and New York. The visual simulation model also provided good detail of an FAA-designed vertiport and airfield at Calverton and the Hudson River Passenger Ship Terminal at 50th Street in West Manhattan.

Microwave Landing System (MLS) Model. The MLS model used in the simulation imitates the MLS standard specified by the FAA. The vertical scan of the MLS system extends from ground level to 35-deg, which provided adequate coverage for the tiltrotor glidepaths investigated.

Model of FAA Microwave Landing System



Flight Director Position Data. Conventional flight director systems show the pilot the desired attitude of the aircraft. For this study, the flight director system operated differently, as it was based on a preliminary version of the V-22 flight director and guidance system and was created from available equipment on short notice. The flight director model used for this simulation used the MLS position data to determine deviation from the desired flight path. Guidance processing generated steering commands that presented the pilot with three cues (longitude, lateral, and power) to move the cockpit controls, rather than showing the pilot desired aircraft attitudes, as a conventional flight director would. The pilot would then move the commands in the indicated direction to maintain the moving command plane symbol within the fixed flightpath vector symbol. By maintaining this alignment, the pilot was able to adhere to a desired flightpath.

Even with the resulting less-than-optimal flight director system, steep approaches could be flown. Additional development work is needed to develop a flight director system optimized for the commercial tiltrotor mission.

Pilot Evaluations

The six pilots participating in this task came from Bell Helicopter Textron, Inc., Boeing Commercial Airplane Group, Boeing Helicopters, the Federal Aviation Administration, and the National Aeronautics and Space Administration. Two of the pilots had no previous tiltrotor experience; four had experience with the XV-15 or the V-22. All had both rotary-wing and fixed-wing experience; the amount of versus rotary experience covered a wide spectrum.

Two sets of piloted simulations occurred in May and June 1990. Five pilots participated in each simulation set. During the first set, pilots became familiar with the CTR configuration and the approach profiles. The first simulation set focused on 3-, 9-, 15-, and 25-deg glideslopes.

The second simulation set included the first set's 3-, 9-, 15-, and 25-deg glideslopes and added 6-, 12-, and 20-deg glideslopes. Approach profiles were also modified in the second simulation set as a result of techniques developed during the first set.

A major modification in the second simulation set was the fuselage attitude on the 25-deg glideslope. As flown in the first set, fuselage attitude prevented the pilots from seeing the vertipad during the 25-deg descent. For the second simulation, nacelles were rotated to 96 deg, lowering the nose of the fuselage so the pilots could see the vertipad when they reached critical decision height. This complicated the landing task, however, as the nacelles had to be rotated to 90-deg (to level the fuselage) before landing gear touchdown.

Another change was made in the second simulation set, in response to pilot comments that the closure rate was too high on the 9-deg approach profile. Nominal airspeed was reduced from 50 knots to 45 knots for the second set of simulations.

Other changes made for the second set were—

- Improved flight director control laws at very low speed.
- Improved visibility of instrument displays and improved control stick force-feel system.

Simulation Procedures. Each simulation session included a pilot briefing, a cockpit-familiarization period, data acquisition, and a pilot debriefing.

Based on information retrieved during the first set of simulations, a test matrix was developed to evaluate the approach profiles. Each pilot flew four cases on each of the seven glideslopes. All runs were conducted at a simulated gross weight of 46,230 lb.

Pilot Ratings

The Cooper-Harper pilot rating scale is a standard industry tool that enables subjective pilot opinion to be handled quantitatively. The scale is similar to a computer decision flow diagram. After completing a task, the pilot responds to questions about the task with "yes" or "no" answers.

Ratings for each level of flying quality were based on airplane characteristics and pilot compensation required to perform tasks. A pilot rating of 1 indicated excellent airplane characteristics with little pilot compensation required. A rating of 10 reflected major deficiencies in airplane characteristics, with loss of control during some porton of the task.

Pilots evaluated the landing task in two portions:

- During the first portion of the task, pilots acquired and maintained the desired descent angle under instrument meteorological conditions. Seven different glideslopes were evaluated, along with prescribed airspeeds for each glideslope.
- During the second portion of the landing task, performed under visual meteorological conditions, pilots terminated the task with either a vertical landing to a vertipad or a missed approach procedure.

Two types of flightpath guidance were presented to pilots during the instrument portion of the task. For all approaches, pilots were shown unprocessed position information from a model of a microwave landing system (MLS). On some approaches, pilots also were provided with flight director guidance to acquire and maintain the selected flightpath. The flight director model gave the pilots steering commands to guide them in moving the cockpit controls.

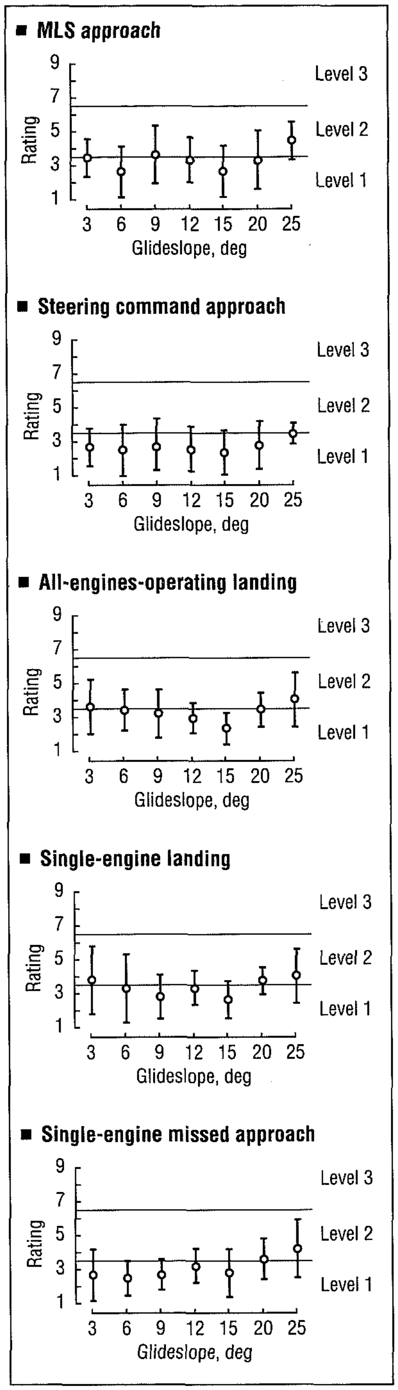
At elevations lower than 200 ft above the ground, simulations were conducted visually, simulating an aircraft breaking out of a cloud layer. Task simulations terminated in one of three ways:

1. The pilots would continue the landing procedure to a vertipad.
2. The pilots would suffer a failure in one engine and would then continue landing with one engine inoperative (OEI).
3. The aircraft would suffer a failure in one engine, and the pilots would abort the landing and execute a missed approach procedure, keeping the landing gear at least 35 feet above the ground.

Quantitative data of aircraft state were recorded for each flight. Adherence to the desired flightpath was measured and processed statistically. For both instrument and visual portions of the approach, pilots rated aircraft handling qualities on the Cooper-Harper scale. These ratings were compiled for each task. Qualitative data were recorded in the form of subjective comments by pilots on task performance, pilot-machine interface, and operational procedures.

Pilot evaluations of the approach task produced borderline Level 1 to Level 2 ratings for most glideslopes, using MLS position data only. When using flight director guidance, the average ratings were Level 1 for all glideslopes except the 25-deg glideslope, indicating that performance was adequate without improvement. The steepness of the 25-deg glideslope made it more difficult to track. Except for the 25-deg glideslope, the pilots generally had no more difficulty with steeper approaches than with shallower approaches, whether they were using MLS or flight director guidance.

Pilot's Averaged Cooper-Harper Approach Ratings



Moderately steep approach angles favored

Based on Cooper-Harper ratings and pilot comments, the pilots preferred moderately steep approach angles (9- to 20-deg). Generally, they felt that vertical landings from these approach angles were easier to accomplish and required less pilot activity. Approach angles of 12- and 15-deg were especially favored because of the ease of deceleration, which required no nacelle tilt; several pilots commented that landings from the 12- and 15-deg glideslopes were "quite comfortable." Shallower angles were more difficult because of the higher workload required to decelerate from the higher speeds associated with the shallower angles and because of the nacelle tilt required to bring nacelles to vertical for touchdown.

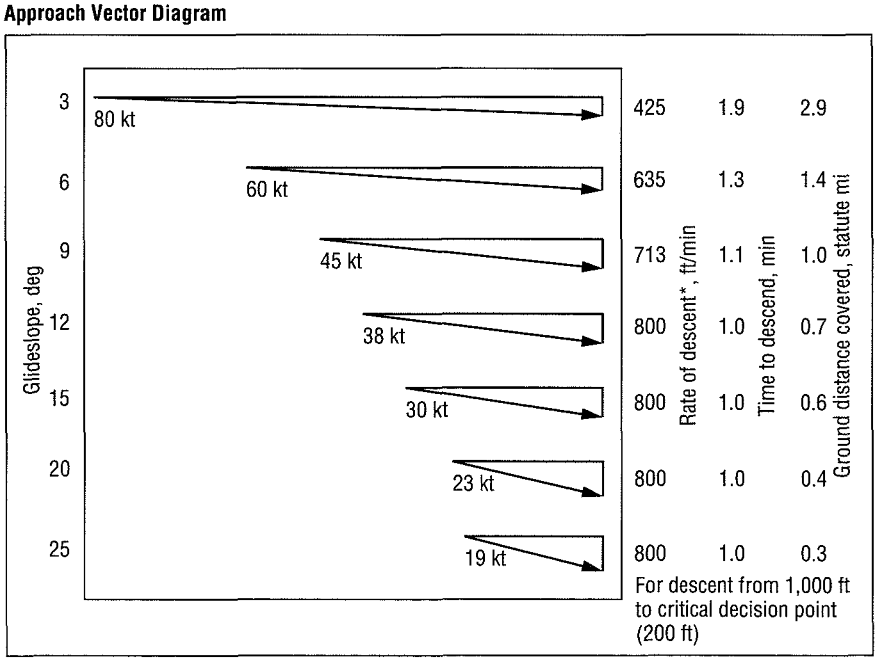
The steepest angles also imposed a higher workload because of the nacelle tilt needed to bring nacelles to vertical for landing. The 25-deg approach angle also required aft nacelle tilt to achieve a nose-down attitude so the pilot could see the landing zone over the nose of the aircraft. When close to the vertipad, the pilot would then need to rotate the nacelles forward to vertical before landing.

The pilot ratings for all engines operating approaches showed a clear preference for the 15-deg approach.

Conclusions and Recommendations

Over a wide range of glideslopes, instrument approaches appear to be feasible with MLS or flight director avionics. The slow approach speed, level fuselage, and high visibility afforded by glideslopes in the 12- to 15-deg range were felt to be conducive to pilot confidence, passenger comfort, and flight safety. The ground distance covered and time required for 12- to 15-deg descents are significantly less than is true for shallower approaches. Intuitively, this seems to offer potential benefits with respect to community noise as well.

Approach Vector Diagram



Glideslope of 12- to 15-deg is ideal for pilots, passenger comfort, and small noise footprint.

Further research required

The results of this study indicate that instrument approaches to vertiports may be feasible, even at moderately steep approach angles. A number of issues need further study to confirm the feasibility of steep approach angles for commercial tiltrotor operations. For instance, the effects of crosswinds, tailwinds, and turbulence at the low speeds at which these approaches are conducted should be examined. Accurate low-speed sensors also would be required for the steep approach angles.

Comments from the pilots also indicate that an improved pilot-machine interface is warranted to ease pilot workload and increase operational safety. They suggested improvements to the instrument displays, nacelle tilt control, and rotor thrust control. Pilot responses gathered during the study also indicate that more complex flightpaths are desirable, including segmented or curvilinear approach profiles with simultaneous reconversion to the helicopter mode; these should be examined through flight simulation. The flight director guidance and the automated modes of the flight control system to support these precision instrument approaches will need to be developed. Future studies should use more pilots to test operational concepts against a broader range of pilot experience. Development of microwave landing systems and/or global positioning systems for navigation, coupled with surveillance and control systems, is essential to the success of a commercial tiltrotor transportation system.

Background

The technology to produce a successful commercial tiltrotor is clearly emerging. But focusing solely on the technology and the aircraft, although they are important, is not sufficient. As the world's civil airspace system now exists, the tiltrotor's potential to reduce ground and air congestion cannot be realized.

Commercial fixed-wing aircraft need runways several thousand feet long, are limited to shallow approach paths, and operate from large, centralized airports; the entire airspace system has evolved around and is structured to those needs. Lacking an airspace infrastructure tailored to exploit its unique capability, the tiltrotor is "just another helicopter" operating in a fixed-wing world.

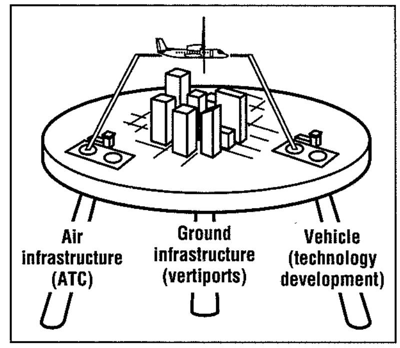
Left to business as usual, without a paradigm shift, decades could pass before the system would evolve to allow CTR's potential to be tapped, while national resources are wasted—in a holding stack over Chicago, waiting for a slot out of LaGuardia, or stuck in traffic on an access road to Washington National.

The question to be faced is: whose problem is air and ground congestion? Air carriers claim that it is not theirs. The FAA charter is directed first to safety, second to capacity. Airport operators' interests are local, not national, in scope. Manufacturers build only those aircraft that airlines will buy. The fact is, the entire nation suffers; it's everyone's problem.

The flight validation plan that follows is not "business as usual." It is a plan that recognizes the symbiosis of technology and its infrastructure. It is one way—there may be others—of stimulating the evolution of a commercial tiltrotor system. The plan reflects the institutional problem: getting all the pieces to come together at one time, pieces over which no single party has jurisdiction or control. In this situation, a new approach is needed, a partnership of public and private interests. Everyone has a role, working together to find solutions.

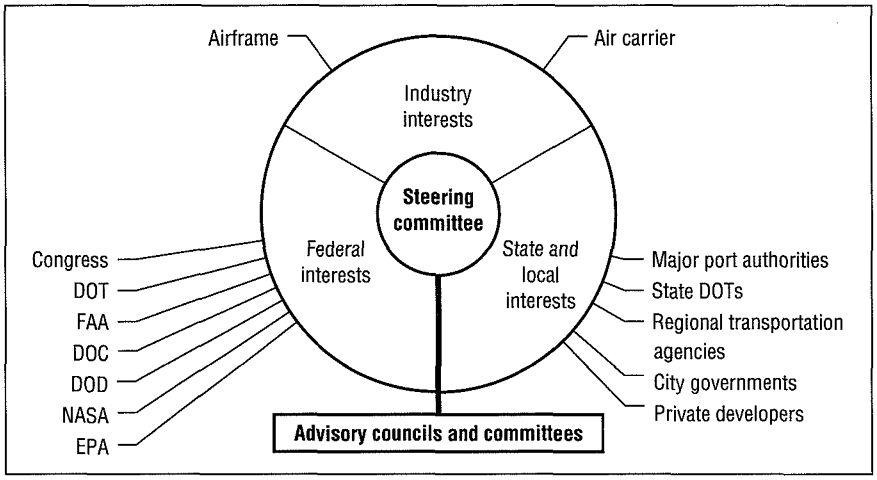
The plan has a single purpose: to describe what must be done to create an initial commercial tiltrotor system within the United States by the turn of the century. The plan focuses on an initial 4-year partnership of Federal and State governments, local interests, plus industry—all working together to evolve tiltrotor technology while determining the ability of each "leg of the stool" to carry its share of the burden. The partnership is designed to determine system feasibility by January 1, 1995; if the decision is affirmative, the partners would proceed in their respective roles and traditional funding relationships. Federal financial participation would be limited to the initial period. If agreements cannot be reached, the partnership would be dissolved.

Supporting Elements of Commercial Tiltrotor System



"Congestion... the entire nation suffers; it's everyone's problem."

Public—Private Partnership



Such a partnership appears consistent with U.S. policy, legislation, and international economic challenges. Federal funding of the development or production of a commercial product is not proposed. The partnership program has three parts:

- Traditional support of basic aeronautical research, as provided for decades in this and other countries.
- Innovative research and development funding for airway and airport infrastructure, to be spent by government in an integrated fashion oriented to improving the productivity of the entire system, instead of research and development sponsored in the normal piecemeal fashion.
- Participation with the private sector in precompetitive research into generic, enabling technologies that have the potential of contributing to commercial applications.

Expenditures supporting the proposed partnership can be structured so as to not violate U.S. policy or GATT agreements. These expenditures will lead to the timely development of advances needed to bring a complex system into being.

If such a partnership were established, the Department of Transportation clearly has an obligation to leadership participation:

> *"The Secretary of Transportation is empowered and directed to encourage and foster the development of civil aeronautics and air commerce in the United States and abroad."*
>
> —as amended, Pub. L. 89-670 #6(c)(1), Oct 15, 1966, 80 Stat. 937

Likewise, the FAA and NASA are critical infrastructure and technology partners, respectively. All Federal funds would be managed by an appropriate agency designated by the Federal Government. That agency would provide program management to guide the efforts of the participating parties.

The study team purposely avoided nominating particular partnership tasks and specific funding details; these issues are inappropriate at this time. It is the idea of a commercial tiltrotor public-private partnership that needs to be debated, not the operational details.

Partnership Objectives

These specific partnership goals are proposed:

- Achieve a common level of understanding and agreement among the partners.
- Further evolve, demonstrate, and validate tiltrotor technology.
- Match the emerging civil product with market requirements.
- Bring the air carriers, public, and local governments to an acceptable level of confidence.
- Validate tiltrotor system worthiness, and gain commitments from local, regional, State, and Federal governmental units to support implementation of a national civil tiltrotor network.

Components of Flight Technology Plan

Technology validation requirements

Air carriers view the CTR as an unproven technology and require certain operational characteristics in any tiltrotor system:

- Safe, reliable, quiet CTR aircraft.
- Competitive operating economics.
- ATC system unconstrained by fixed-wing limitations.
- All-weather operations.

NASA research. Continued research is needed on pilot-machine interface, external noise, air traffic control integration, certification, improving payload fractions, internal noise, and one engine inoperative alternatives.

Two XV-15s. The XV-15s would be used to validate noise prediction research and infrastructure development (TERPS and routes) and to research pilot workload reduction concepts.

Two V-22s. The V-22s would be used for—

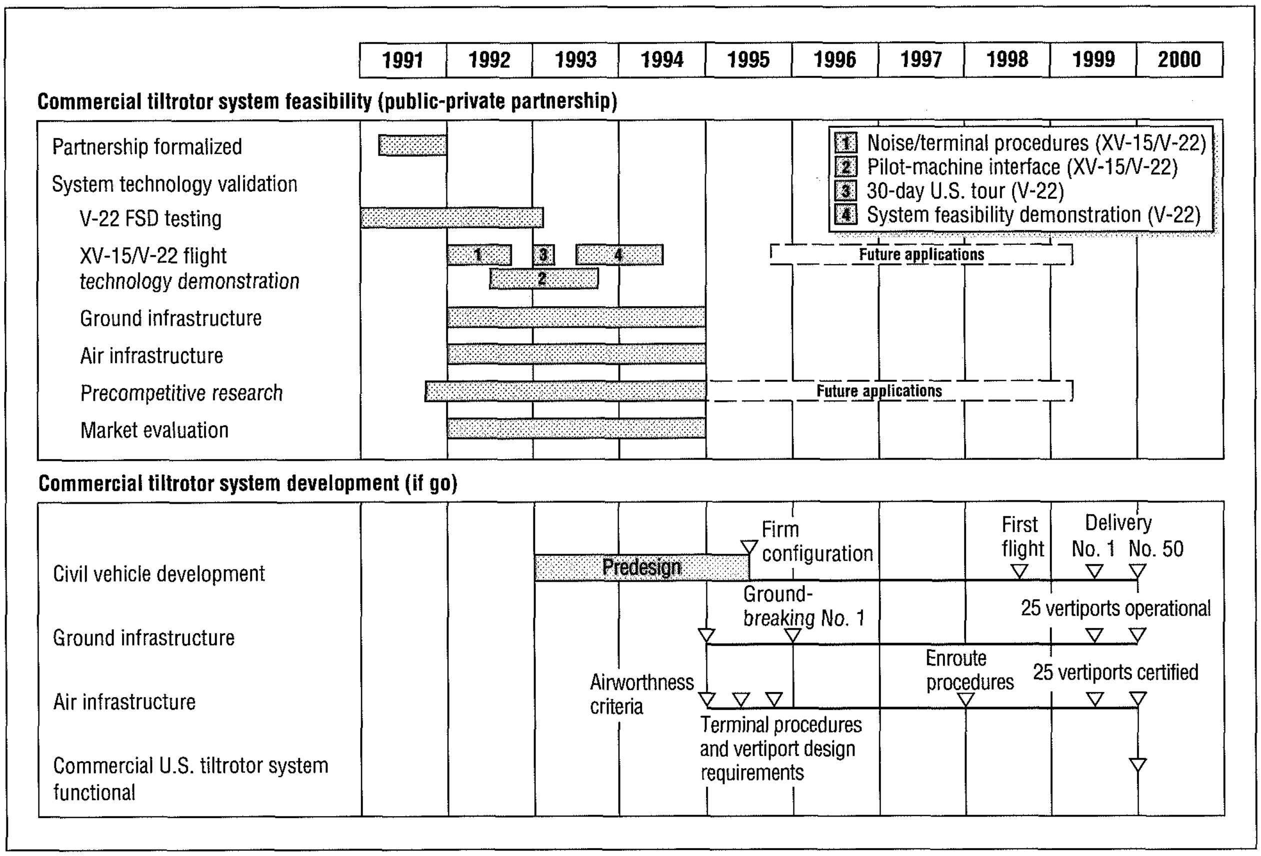
- 30-day North American demonstration tour.
- Package express inservice demonstration by a selected operator in the Northeast Corridor or the southern California Corridor.
- Terminal area and enroute ATC and operations, external noise reduction, flight profiles, flight safety and certification studies, and demonstration of pilot-machine interface capability.

Flight simulators. Simulators would be used to research and demonstrate operational flexibility, approach and takeoff patterns, TERPS development, CTR design modifications, missions for preliminary certification, pilot-machine interface, and facility design (city center and airport vertiport infrastructure).

Wind tunnel testing. This testing would verify improvements in drag download, and aeroelastics, as well as rotor noise and performance testing. Methods of cabin noise and vibration attenuation would be researched.

Engine and transmission ground tests. The engine and transmission package would be tested as part of the validation program. Active noise suppression methods would be optimized.

Commercial Tiltrotor System Milestones



Commercial configurations—preliminary designs

To achieve a functioning commercial tiltrotor system by the turn of the century, production leadtimes require that available aircraft technology be "frozen" in mid-1995. As a practical matter, the aircraft must lean heavily on V-22-developed technology, plus (1) lessons learned from building and testing the V-22 FSD aircraft and (2) information generated by research conducted until the configuration freeze date. The timing issue requires that basic and precompetitive research efforts until mid-1995 be focused on technology that has the potential to benefit the "turn-of-the-century" configuration. After that point, research efforts can shift to longer term issues. The configuration implications are—

- Year 2000 configuration: V-22-based technology, plus focused research.
- Beyond year 2000: "Clean sheet of paper"—any size, any market.

Infrastructure development

The success of the flight technology validation plan depends not only on the technical and operational characteristics of the CTR airplane but also on certification, infrastructure provisioning, airspace compatibility, environmental sensitivity, and community satisfaction. Both ground and air infrastucture need to be developed.

Ground Infrastructure. Ground infrastructure development must occur simultaneously with flight technology validation and FAA air infrastructure activities. These ground infrastructure development activities must be completed by the go-ahead date:

- Consolidate FAA-funded vertiport studies.
- Validate FAA/DOT 14 CFR Part 150/53 vertiport and vertistop design criteria and recommendations.
- Complete preliminary assessment of vertiport locations and FAA Vertiport Location Guide.
- Complete environmental studies.
- Revise vertiport design guides to reflect evolving CTR capabilities and requirements.
- Establish formal coordination structure among design teams working on the CTR airplane, ground infrastructure, and air infrastructure.
- Schedule network vertiport planning and development.
- Fully develop search for private capital for vertiport construction and operation.
- Act on public input during infrastructure development.

Air Infrastructure. These major tasks need to be completed:

- Flight technology validation plan participation and support.
- Certification criteria of production airplane.
- National Airspace System development.
- Air infrastructure development. Data and implementation plans must be ready to support CTR airplane operations in 1999.

Commitment Criteria

The proposed 4-year plan calls for determining CTR system potential by January 1, 1995. These criteria for commitment to developing a national tiltrotor transportation network must be achieved by that date:

- Continued progress on the V-22 program.
- Expression of interest from certified air carriers in sufficient quantity to justify industry development.
- Agreement by the Port Authority of New York/New Jersey, MASSPORT, the Metropolitan Washington, D.C. airports, and the City of Philadelpia to form a consortium or joint venture to create an off-airport vertiport system in the Northeast Corridor.
- Commitment by affected airport authorities to on-airport vertiports.
- Agreement by local governments and major cities to provide leadership in vertiport location and operational guidelines.
- Completion of a NASA research program supporting CTR technical definition.
- Agreement by the Department of Defense to release two V-22 Ospreys for technology validation and demonstration purposes.
- Early agreement by the FAA to (1) develop vertiport-aircraft communications, navigation, and related systems; (2) install appropriate facilities at vertiports, including vertiport navigation systems; (3) provide clear airspace enroute and in close proximity to vertiports; and (4) support the testing and certification of the CTR aircraft and vertiports.

Beyond the Partnership

The formal partnership formed to "fast-track" the evolution of commercial tiltrotors has a 4-year job. But the teamwork between American industry, local government, the FAA, and NASA—which for decades has created superior American aircraft and a second-to-none air transportation network—would continue. Each team member would have its traditional role: industry to build the aircraft, local government to form the ground infrastructure, the FAA to develop the air infrastructure, and NASA to push the boundaries of tiltrotor technology to be applied to the next generation of tiltrotor aircraft.

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16. Abstract
Phase II of the study examined the commercial passenger market for the civil tiltrotor. A market-responsive commercial tiltrotor was found to be technically feasible, and a significant worldwide market potential was found to exist for such an aircraft, especially for relieving congestion in urban area-to-urban area service and for providing cost-effective hub airport feeder service. Potential technical obstacles of community noise, vertiport area navigation, surveillance, and control, and the pilot/aircraft interface were determined to be surmountable. Nontechnical obstacles relating to national commitment and leadership and development of ground and air infrastructure were determined to be more difficult to resolve; an innovative public/private partnership is suggested to allow coordinated development of an initial commercial tiltrotor network to relieve congestion in the crowded US Northeast corridor by the year 2000.

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