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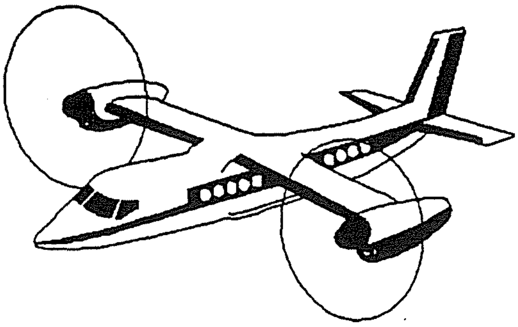
Research Needs for a Commercial Passenger Tiltrotor



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Research Needs for a Commercial Passenger Tiltrotor

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Abstract

The National Aeronautics and Space Administration (NASA) recently completed a series of contracts and studies that examined the technology needs for a tiltrotor aircraft in commercial service as well as military missions. The commercial needs arise out of market-driven requirements that include vertiport location and design, passenger comfort levels and competitive costs. The military needs are derived from time-sensitive missions and combat effectiveness. In response to these results, NASA has decided to address the commercial needs first, recognizing that there will be eventual payoff to military missions as well. Research goals were explored in acoustics, flight dynamics, human factors & displays, dynamics and loads, propulsion, safety, and configuration design. The paper describes the development of these goals from the market requirements and the implications for possible research activities. The aircraft issues that were addressed include number of blades, advanced blade planforms, steep approach requirements and pilot-cockpit interface for civil operations.

Background

The NASA charter for aeronautical research focuses on long term, high risk research that would not otherwise be funded by private industry. In planning the research program at NASA, the agency sponsors studies that examine both the promise of and the market benefits from technology development. In 1990 NASA co-sponsored a study of the commercial passenger tiltrotor market with the Federal Aviation Administration (FAA). Boeing Commercial Airplane Company conducted the effort with its partners, Bell Helicopter Textron, Inc., and the Boeing Helicopter Division (reference 1). The government was particularly interested in the technologies that are necessary for civil use, that built on the development of the military V-22 Osprey and are unique to commercial passenger operation. That study defined the requirements for an ideal set of vehicle characteristics which, if feasible, could capture over 2600 aircraft sales after the turn of the century. These characteristics were not necessarily those of a derivative of the V-22.

Of course, a near term derivative of the V-22 will have a place in that market, and its development will be a near term business decision by industry. NASA would interact with that activity through the FAA in the development of criteria and standards, and through use of its national facilities and expertise. But by design, NASA is also interested in technologies that could be developed in the long term for use in a more commercially competitive design. For instance, one of the conclusions of the commercial study was that vertiports must be able to be located in high demand centers in order to be cost competitive with existing air transport. That means that the vehicle must be a quiet neighbor and must use the least possible clear space both on the ground and in the air.

NASA also sponsored High Speed Rotorcraft Studies with the four major U.S. helicopter companies (references 2-5). The studies analyzed the potential of the current and improved technology to achieve a 450 knot speed in an efficient design. Both civil and military missions were considered. Tiltrotor and tilt wing designs were favored by several contractors for the transport missions. The effect of speed and technology level were studied in some detail in order to quantify promising research areas.

NASA Direction for High Speed Rotorcraft

The NASA response to these studies is still evolving. Nevertheless, the critical issues have been defined. Research planning is underway. NASA concluded that 450 knot cruise speeds were too ambitious at this time and resulted in a very complex vehicle, even for high priority military missions. (The Department of Defense is also conducting its own studies which may re-evaluate this conclusion.) For the civil passenger mission, however, the push for increased speed identified several promising tiltrotor technologies including swept blades and variable diameter rotors.

NASA has chosen to concentrate on the commercial passenger transport market (Figure 1, reference 1). This market meets a clear national need for alternatives to capacity limits at congested airports. The market is projected to be large and is sensitive to vehicle technology improvements.

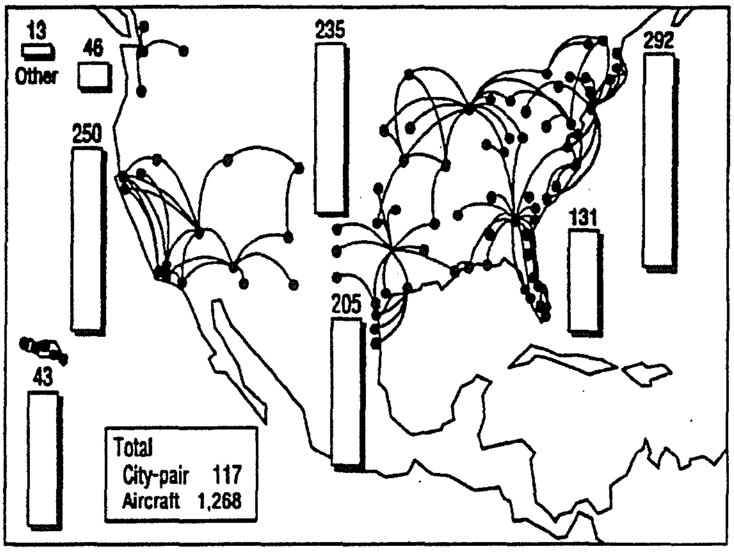


Figure 1. Tiltrotor passenger market, year 2000 (N. America)

Clearly, this is an opportunity for NASA to address long term, high risk research in support of a future decision by U.S. industry to develop a more "market-responsive" vehicle that may be significantly different from a V-22 derivative. Accordingly, this paper will cover some of those technologies that are driven by market need. Those needs are grouped as follows:

- community and passenger acceptance
- civil flight systems safety
- commercial economics.

Community Acceptance

Vehicle Exterior Noise

How quiet does a commercial tiltrotor have to be? (In cruise, the aircraft design is inherently quieter than any other helicopter or turboprop now flying. This is one of the strongest reasons for proposing the tiltrotor in this role at the outset.) Certainly if a large number of vertiports is required to meet the traffic demands, then some of these may be near residential neighborhoods. Using established metrics for this type of operation, a noise goal would be the 24 hour metric of 65 Ldn within a prescribed noise-sensitive boundary. To achieve a desired capacity of 500,000 passenger per year, this 65 Ldn would have to be met by a 40 passenger tiltrotor operating some 50 flights a day at 65% capacity.

Larger vertiports would require less noise-sensitive locations or wider noise boundaries - but would still need a quiet aircraft to minimize the impact. The critical flight condition is final approach. Figure 2 represents the noise footprint made by the XV-15 in approach under 65 Ldn criteria. It is based

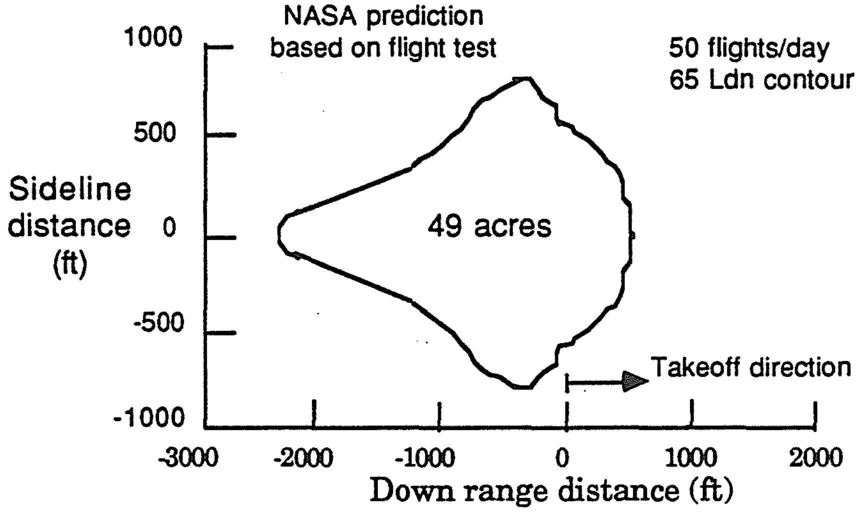


Figure 2. XV-15 noise footprint in approach (original blades)

upon experimental data gathered by the XV-15 with its original blades (NASA calculation). The advanced technology composite blades (ATB) now flying on the XV-15 are 3-5 dB quieter in overall sound pressure level in hover (reference 6). Figure 3 demonstrates the impact of redesigning the V-22 with this blade technology and again with variations in tip speed and disc loading and number of blades (reference 7). (The flight number limitation is for residential areas measured directly under the flight path 500 feet from touch down; business or industrial limits would be much less restrictive.)

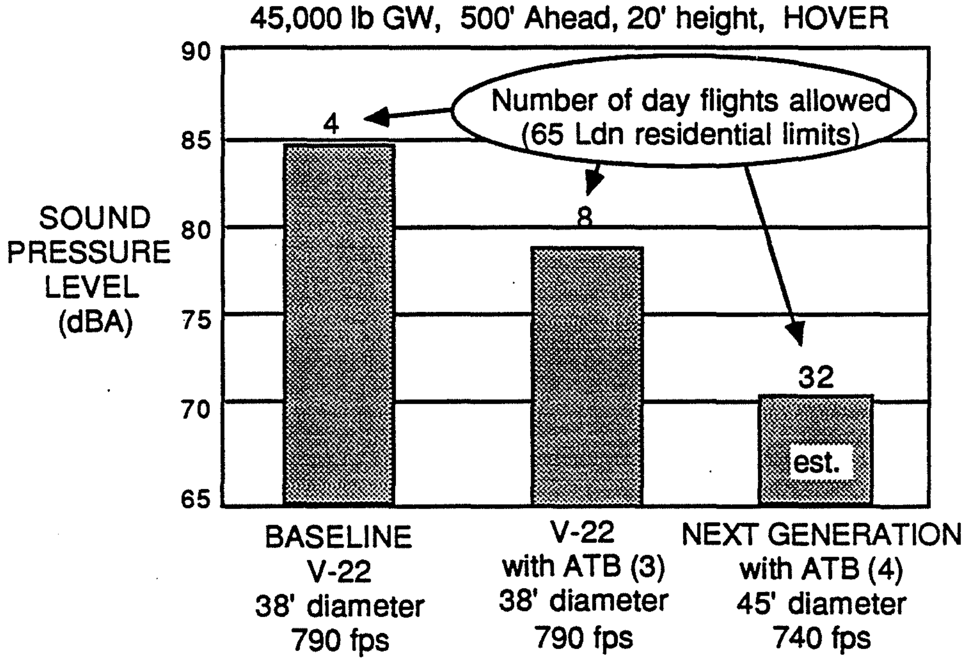


Figure 3 Noise levels vs. allowable flights

Obviously, this last redesign will compromise performance and weight. An ambitious research goal would be to achieve a 6 dBA reduction with minimum penalty. Flight testing of a new rotor would be needed to validate this reduction.

Although not as powerful as reduced tip speed, using more than 3 blades per rotor for noise reduction is relatively easy to define. Blade number effects the nature and frequency of the noise as well as vibration at the hub. Unfortunately, it is not clear what kind of hub configuration is possible with 4 or more blades. Requirements for pitch-flap coupling for rotor/wing stability result in problems with pitch link clearance as illustrated in Figure 4. The pitch-flap coupling is equal to the tangent of the delta 3 angle, which is the angle between the effective flap hinge and a line perpendicular to the blade pitch axis. Studies have shown that this angle should not exceed about 15 degrees. (The EUROFAR design has proposed an interesting 4-bladed solution that is called a homokinetic gimballed hub (reference 8). But it is an untested configuration in large scale.) It is not clear that 4 or more blades are needed if three can be made sufficiently quiet. Hence, the tradeoffs, including the benefit of reduced vibration, should be analyzed early.

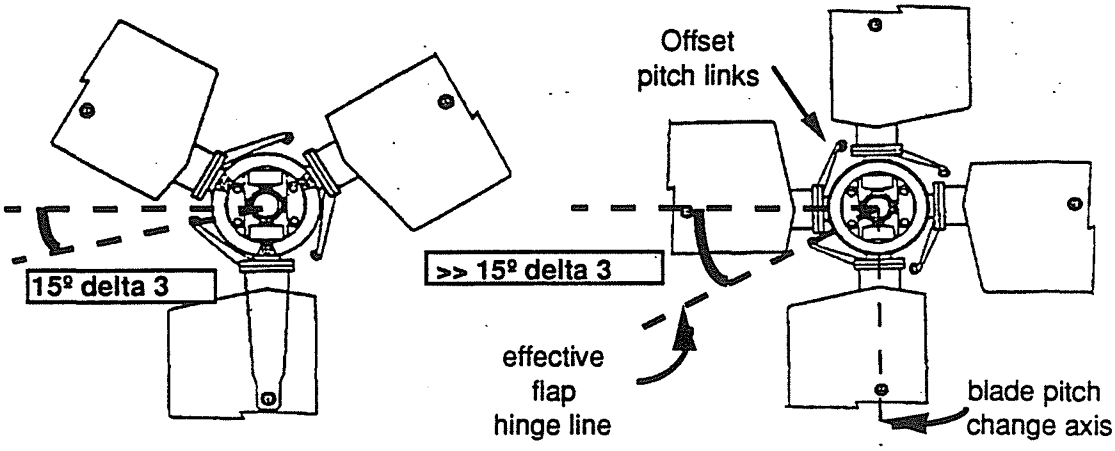


Figure 4. 4-bladed hub with excessive pitch/flap coupling

Noise Abatement using Steep Approaches

Noise abatement maneuvers such as steep approaches may be a lucrative area for achieving a reduced vertiport noise footprint. Figures 5 and 6 show the effect of varying approach angle on footprint, time and distance - parameters critical to noise exposure. Currently, helicopters under instrument conditions are permitted to fly 4-6º approaches in a stabilized

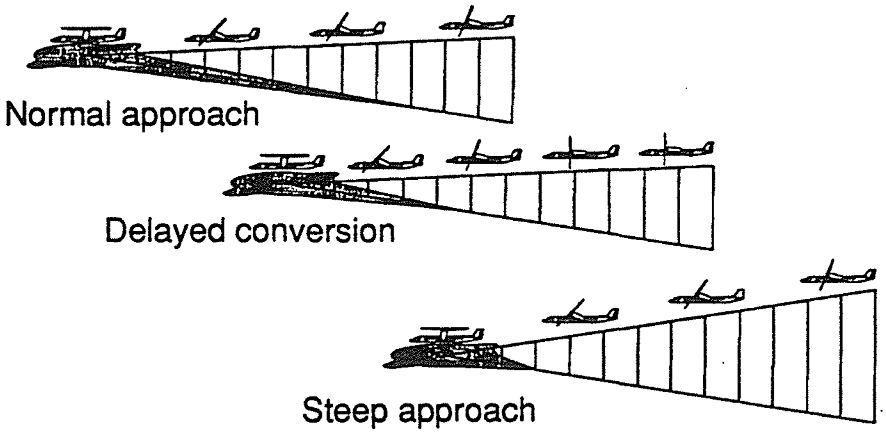


Figure 5. Noise footprints for several abatement maneuvers

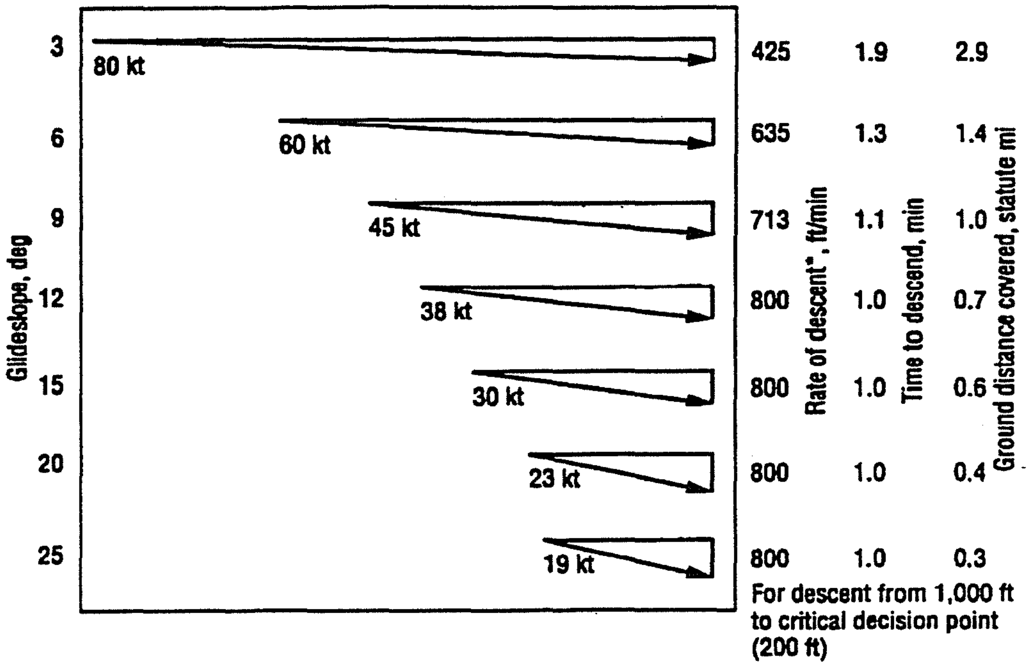


Figure 6. Effect of steep approaches on noise exposure

configuration on final approach. The latest FAA Advisory Circular of Vertiport Design (draft, reference 9) proposes 9º as a standard for tiltrotor approaches. The circular states clearly the presumption that industry would have to develop a certified aircraft to operate safely at this angle. However, simulation has shown that 15º is not unreasonable as a research goal. Varying nacelle angle on final approach may also yield benefits but requires greater automation and is not now allowed under present FAA instrument rules. The goal for research here would be to achieve an additional 6 dBA reduction in noise through steep approach angles and/or maneuvers. Flight testing combined with analysis and simulation would be needed to demonstrate feasibility.

Steep operations have the benefit of requiring less intrusion into the airspace of the surrounding community. Again, the limiting condition is approach. (The safety considerations for control and engine failure are much more severe in approach.) In urban centers, airspace is extremely expensive to reserve for flight operations. To a first order, clear space for 3º approaches is 25 times that required for 15º approaches. Recent experience with the heliport at the Dallas convention center reinforced this need (Figure 7, reference 10). The designers found that it was cheaper to build the landing surfaces atop the center - even with the structural penalties - rather than on ground level due to the savings in neighborhood air rights.

Figure 7. Vertiport design for the Dallas Convention Center
(Charles Willis & Associates, Inc., architects)

Passenger Acceptance

Many of us have had "never-again" experiences on certain models of small commuter aircraft, both fixed wing and helicopters. Reasons cited often include interior noise, vibration, seat and baggage room, ride quality and general feeling of safety. A typical commercial tiltrotor flight would last approximately one hour. The passenger has every right to expect an experience similar to current airline transports. A typical layout is shown in Figure 8 that illustrates the features common to a fixed wing transport. Translating this expectation into research goals, therefore, means that the level of noise, vibration, ride quality and feeling of safety must be at least competitive with the best commuter propeller aircraft. Each of these will be discussed in turn.

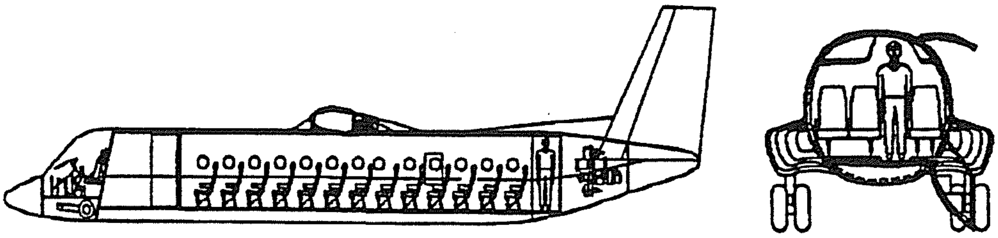


Figure 8. Typical passenger layout for commercial tiltrotor

Interior Noise

Interior noise levels in Figure 9 show a range for different classes of aircraft, from helicopters through large jet transports. For a modern

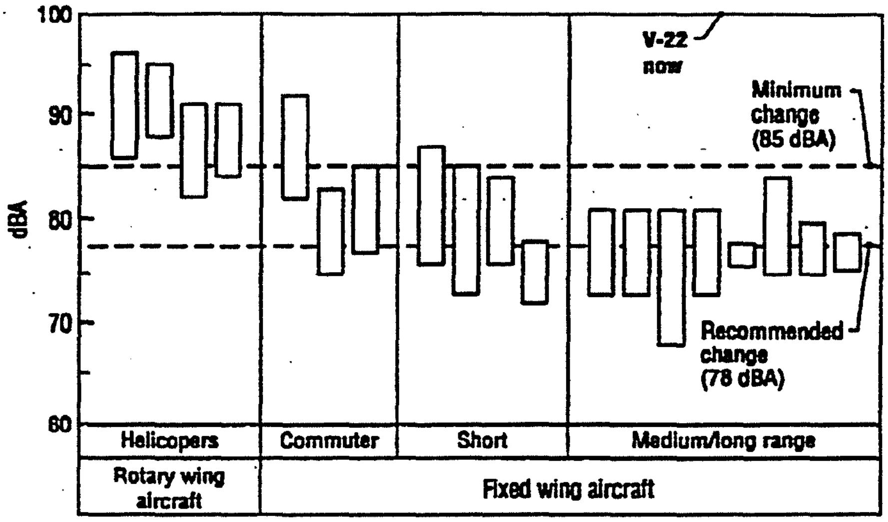


Figure 9. Typical interior noise levels for different aircraft classes

aircraft entering service in the post 2000 year time frame, a goal of 78 dBA is appropriate. Normally, the essential trade for the designer is the weight of the sound dampening to achieve this level. For the V-22 in cruise, the blade passes about 1 foot from the fuselage side at a helical tip Mach number of 0.8. For commercial operations the resulting low frequency noise may be difficult to reduce with conventional techniques. A promising technology underway at NASA involves the use of piezo-ceramic or electric actuators to create anti-nodal cancellation of the primary frequencies. As few as two or three may be needed and could be located inside the fuselage shell on the trim used for passenger service. A low cost bench test of the system could demonstrate this technology's potential.

Other design trades may be needed to meet the interior noise goal. Cruise tip speed and the gap between the tip and the fuselage are variables to consider (Figure 10). The system costs of these changes must be understood before choosing new values just to reduce interior noise.

Vibration

Vibration is also important for the projected hour-long flights. Prior experience with the XV-15 and V-22 has shown that there are means to predict and alleviate vibration. However, the weight penalty has usually been 2-3% of gross weight. The goal of a research program would be to improve the predictive tools for tiltrotors and validate the methods. Targets for vibration should be "jet smooth" or no more than .03 g's using less than 2% of gross weight. This implies building in vibration de-tuning in the wing structure, accurately accounting for such phenomena as tail shake, and evaluating a greater number of rotor blades. An isolated floor similar to the Boeing 234 could meet the .03 g's goal but the increased weight may be significant.

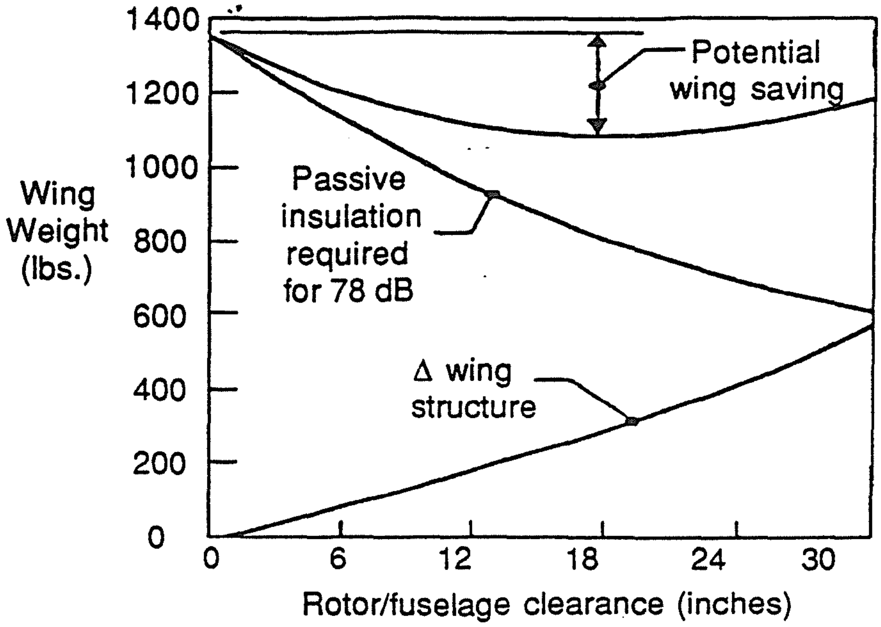


Figure 10. Effect of rotor/fuselage clearance on weight (aeroelastic changes not considered)

Gust Sensitivity

Gust sensitivity for a passenger tiltrotor has not been evaluated to any degree. For rotor hubs that have different pitch/flap coupling, gust response will be an important parameter. While the so-called "chugging" longitudinal motion found in the XV-15 was curable to a first order, little flying has been done in moderately severe weather. With typically lightly loaded rotors in cruise, a tiltrotor must tolerate the statistically worst-case gusts. Flight testing will be needed to demonstrate adequate ride quality.

Active control can further alleviate gust response. Both wing and rotor controls could be integrated in an active control loop to improve ride quality, as well as aeromechanic stability margins and vibration. Trade studies of various control schemes will be necessary to identify their value in the marketplace. However, it seems reasonable to include conventional wing controls for active gust response suppression in any research efforts.

Perceived Safety

The last key area in ride quality encompasses how the passenger views his safety. Conventional airliners have accumulated a body of knowledge on acceptable characteristics for interior space. But the tiltrotor offers a range of fuselage attitudes and possibly steeper descents where there are questions of passenger tolerance. Tiltrotors do not have the STOL problem of severely negative fuselage angles, that, in test programs of steep approaches, alarmed passengers. Indeed, for the tiltrotor, the slower descent speeds for steep approaches may give the passenger a greater sense of safety. Ground-based cabin simulators can answer some of these questions. However, flight demonstration is clearly needed to distinguish between discomfort due to noise, vibration and the perceived safety of the flight.

Civil Flight System Safety

Design for the civil market will mean different qualification levels for many tiltrotor systems. For instance, certification of the primary flight control system for failure probability is more stringent for civil passenger operations than for the military V-22. A new set of standards issued by government certification agencies must be met or shown why exception can be taken without degrading safety. The FAA in the United States has taken preliminary steps in this regard with the publication of Draft Interim Airworthiness Criteria for Powered-Lift Normal Category Aircraft . As previously mentioned, the FAA has also issued a draft Advisory Circular, Vertiport Design. NASA has worked with the FAA in developing these and other standards, and will continue to do so when requested. There are several other safety areas in which NASA traditionally has led. One of those areas is contingency power for emergency engine ratings.

Single Engine Failure

The steep approaches are limited to 800 foot/minute rate of sink based upon previous studies of safe procedures for arresting descent in the event of failures. The crucial failure is the loss of one engine. Traditionally helicopters use limited emergency engine ratings to meet safe operating requirements. However, there is not a clear understanding of the damage process to the engine under these ratings. Engine removal usually follows which requires time-consuming maintenance. The research goal here would be to provide emergency power of at least 125% without the requirement for automatic engine removal.

There are several ideas for achieving this goal, including liquid injection and film cooling, as well as developing a better understanding of how to predict and identify damaged engines. Such capability would enable high levels of engine reliability under the typical power demand profiles of tiltrotor operations. The causes for removal, even with emergency power use, could be statistically small. Studies conducted in the early 1980's by NASA showed that contingency power rating over 30% were possible (reference 11). Figure 11 illustrates the effect of emergency power rating on gross weight. The challenge for emergency power rating concepts is certification and delivery test acceptance - without a demonstration that might affect engine life. Careful analysis is needed to weigh the various costs of engine modification and proof testing against the penalties of opting for an existing, oversized engine that is already certified.

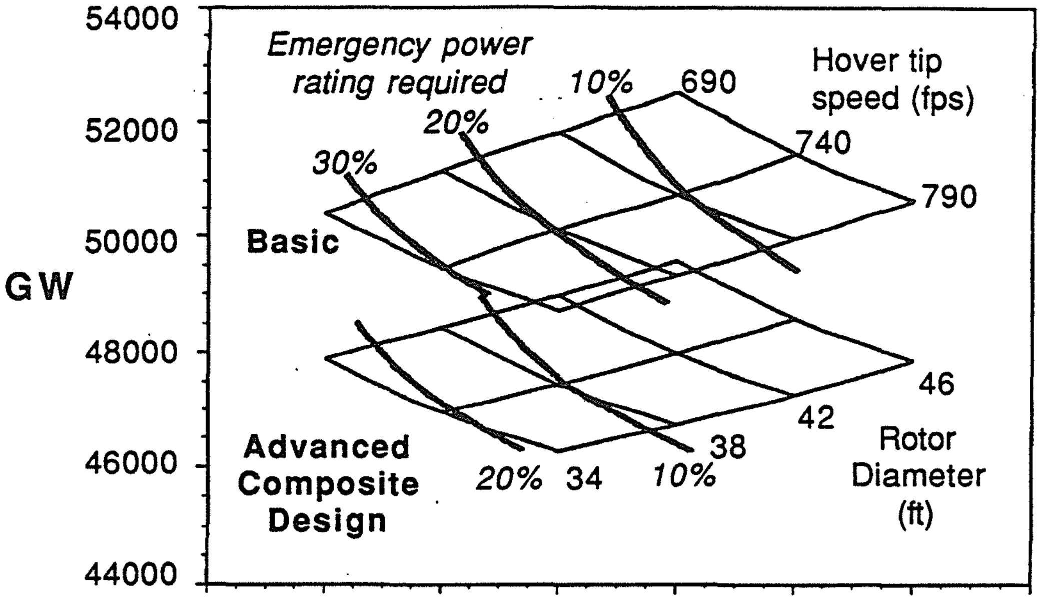


Figure 11. Effect of emergency power and tip speed on weight

Piloting Issues

The layout of a civilian cockpit and the procedures for operating in an air traffic environment present unique challenges for a commercial tiltrotor. Cockpit commonality is becoming the norm for airline operations. The reasons stem from perceived safety factors and the financial gains from minimizing specialized training in a pilot's career ladder. Hence, the displays and controls must reduce the unique interfaces between the pilot and the unique multi-mode characteristics of a tiltrotor. (Figure 12 shows the cockpit configuration for the military V-22.) The best level of automation deserves exploration, especially for terminal operations which use steep approaches and noise abatement maneuvers, in wind and turbulence. An obvious goal of this research would be Level 1 handling qualities in simulated operations and emergencies.

Less obvious is the need for higher level guidance and navigation for terminals located in built-up areas. The possibilities are only limited by cost. Active obstacle avoidance is under investigation by NASA with the U.S. Army and could apply to urban operations. Similarly, terrain or obstacle representations for selected vertiports could be pre-programmed like current cruise missile guidance. Satellite-based navigation is also under discussion but requires demonstration for safety and cost. The cost must be studied on a systems-wide basis. The example of Ransome

Airlines use of on-board remote area navigation to pioneer direct air routing for STOL commuters might be applicable to this area.

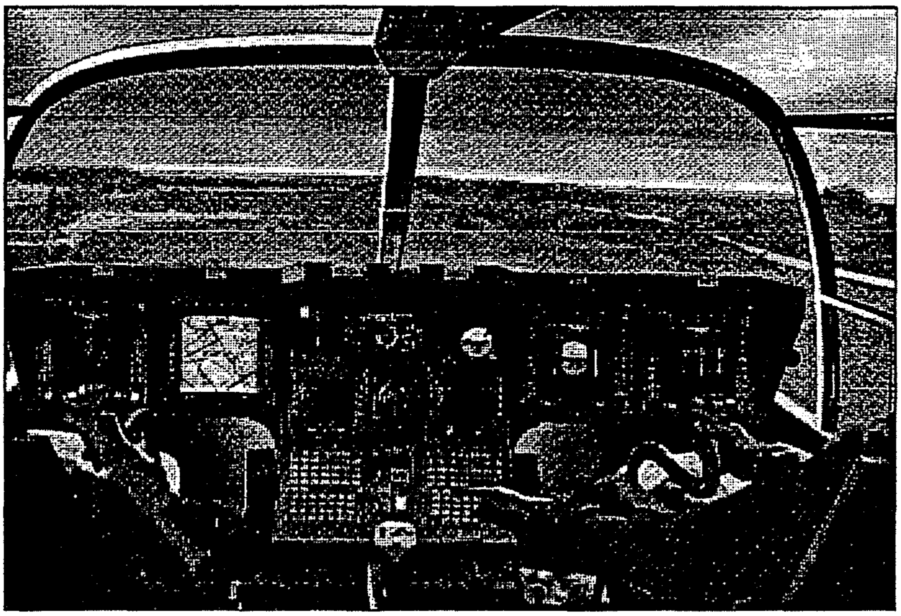


Figure 12. V-22 cockpit configuration (artist's rendering)

Commercial Economics

The word "commercial" has been used in this paper to imply a profitable enterprise available to the paying public rather than "civil" which could cover public service use such as police or rescue. This is not to imply that the government has no role in a market venture. The various government levels shape the market through taxes or tax abatements, credits, landing fees, low interest loans, regulation of anti-trust, liability, environmental impact, land and airspace usage, and imposition of tariffs and duties. Indeed, the roles of the FAA and the Department of Defense shape the market, too: air traffic control, regulation and safety; and national defense. The role for NASA, as stated earlier, is high risk, long term research. This is especially important for a new type of aircraft that faces a multitude of challenges in addition to technical risk: certification and regulation, operational guarantees, and acceptance by the operators, customers and the general public near vertiports.

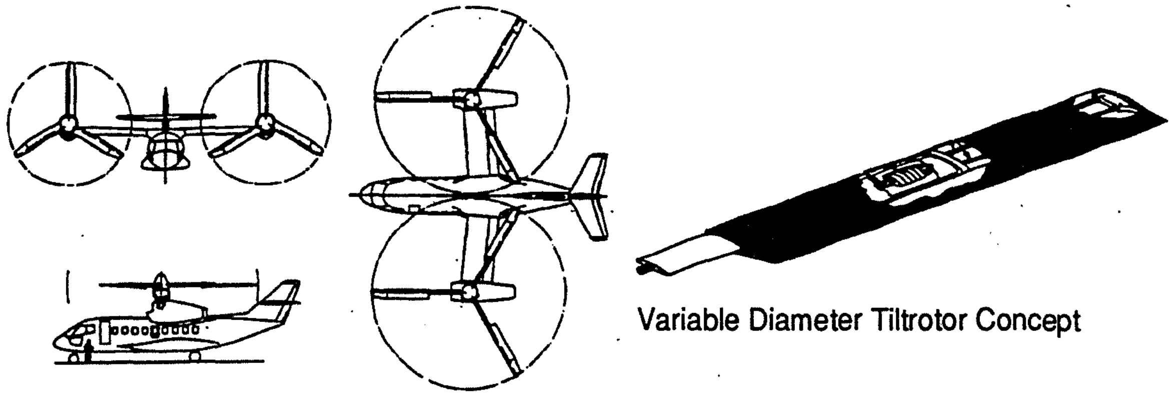
Practical Vehicle Costs

The high risk of certifying a new type of aircraft can lead to a conservative approach to design. Aircraft manufacturers have produced a family of designs all under the same basic model number. New wings, fuselage stretching, cockpits, engines, tail rotors and, yes, main rotors have been certified under the original model designation, since only the changes have to be re-certificated, not the whole aircraft. This may be stating the obvious, but the lesson is not lost on the tiltrotor. The first civil tiltrotor may well be some version of the V-22. The FAA has been asked to witness developmental testing to facilitate initial certification. For an advanced tiltrotor which may be targeting a larger market, the conservative approach may result in the use of existing engines, a metal fuselage, and other compromises that affect weight and ultimately cost. In recognition of that tendency, research should also address performance and weight improvements, but be carefully chosen to reduce risk as well.

Performance

The three main areas of research in this area are engine and transmission efficiency, fuselage drag and rotor performance. Conventional engine and transmission improvements are underway in other programs and beyond the scope of this paper. Little improvement is to be gained from changes in existing tiltrotor parameters such as rpm range, transmission philosophy, or engine location. Fuel savings does not greatly affect weight and cost for short haul operations (unless rules for reserves could be changed through technology). On the other hand, drag reduction is possible and straightforward to implement. The challenge for the aerodynamicist will be to account for drag and loads resulting from interferences between the wing/nacelle, fuselage "hump" and the tail.

A more advanced rotor design is not ruled out just because of risk. It is acknowledged that reduced rotor noise will eventually require a better rotor for commercial operation. The possibilities include an upgraded design based upon the V-22 three blade gimballed hub, four or more blades on an advanced hub, variable diameter blades, and swept blades for high speeds (Figure 13). The merits of these technologies in the marketplace have not been quantified. They may be analyzed in the coming year in a new study sponsored by NASA just now in the proposal stage. Certainly noise reduction with little performance penalty remains the overriding objective. However, there may be ways to improve other parameters such that the system benefits are too attractive not to consider. Cruise speeds of over 350 knots are not unreasonable to aim for (references 2 - 5).



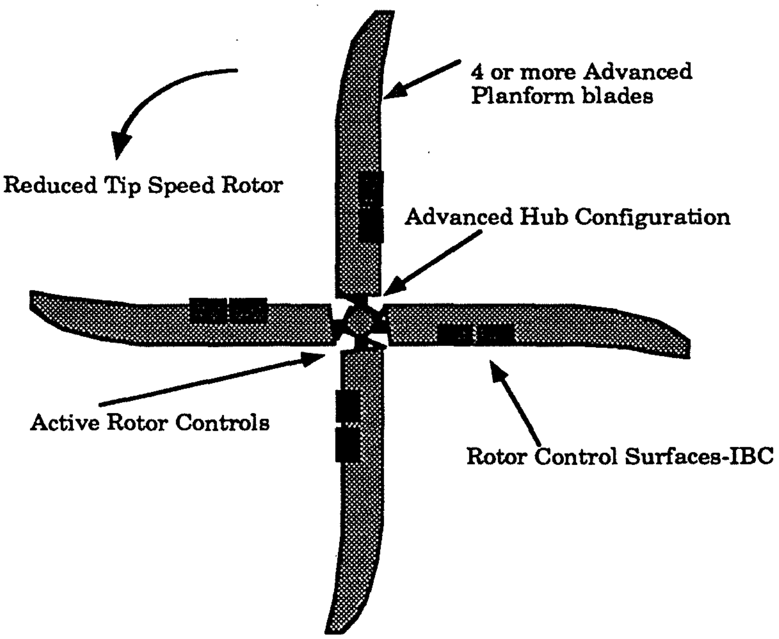


Figure 13. Design technologies: variable diameter rotor, swept blades

One area purposefully left out of this section is wing download in hover. For military missions, significant hover times are an important design factor. Reducing download by 10% usually directly increases payload by a similar percentage. However, in passenger operations little time is spent in hover. Download quickly disappears with 10 to 15 knots of forward speed. It is not clear that download is a factor in engine size, which may be more dependent on approach single engine failure, where the gross weight is less. Nevertheless, every effort should be made to minimize download. A number of concepts (Figure 14) have been evaluated and continue to be analyzed and tested. A goal of 7 to 8% download is ambitious but feasible. The system benefits of any added complexity and weight have to be evaluated.

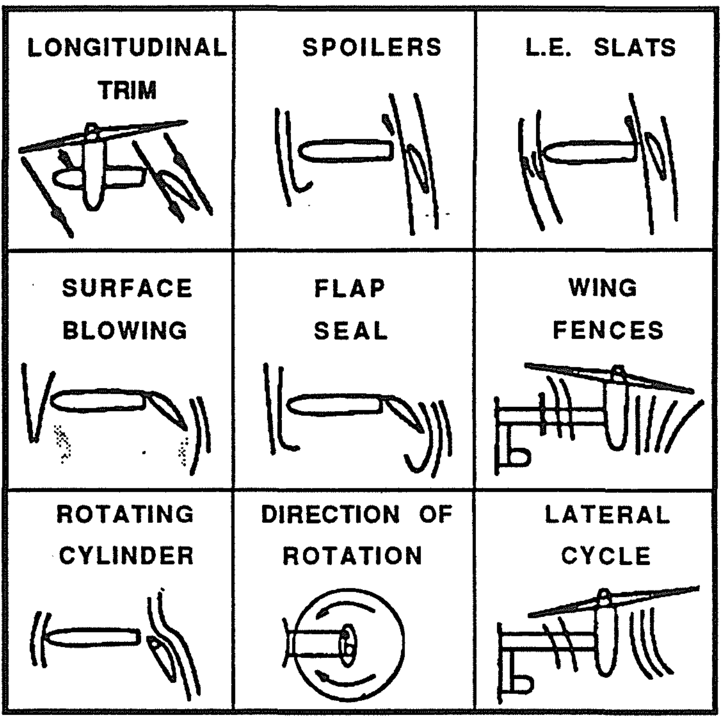


Figure 14. Matrix of download concepts evaluated

Weight

The development of lighter weight composite material and structure is another area that is outside the scope of this paper. But the application of such developments to tiltrotor-unique components is not. Composites offer promise in structural tailoring for the wing aeroelastic modes and the wing/fuselage attachment. The recent NASA studies (reference 2-5) have shown that thinner wings (18% versus 23%) may be possible for the same weight. The effect on drag divergence speed is dramatic (Figure 15).

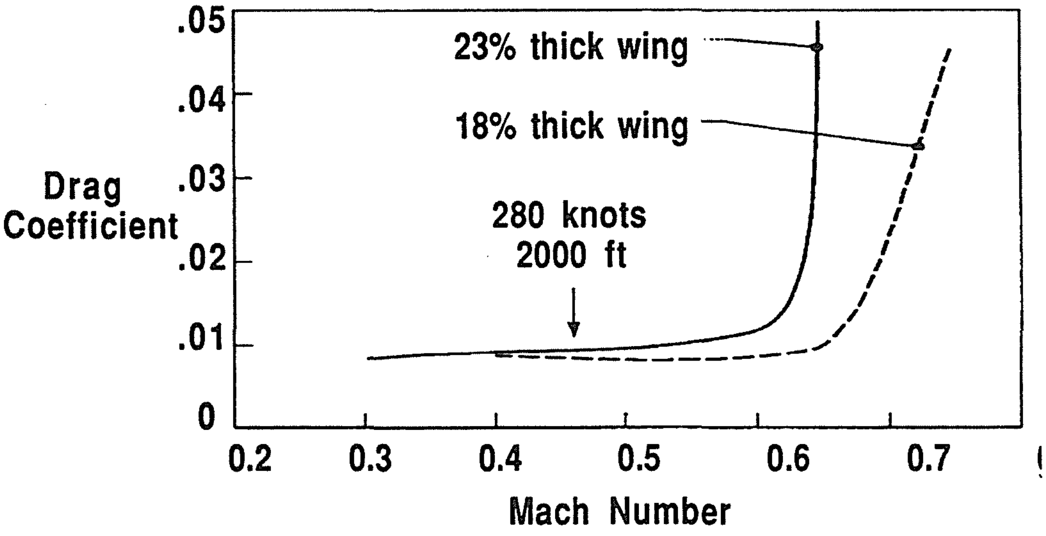


Figure 15. Wing drag versus Mach number for two thicknesses

High Vehicle Utilization Rates

The commercial study (reference 1) postulated aircraft yearly usage consistent with fixed wing aircraft: over 2000 hours per year. For passenger operation, if the utilization were half this goal, the price of the aircraft would effectively double, raising the average ticket price by more than 20%. Figure 16 shows the relationship between ticket price and competitiveness with a turboprop.

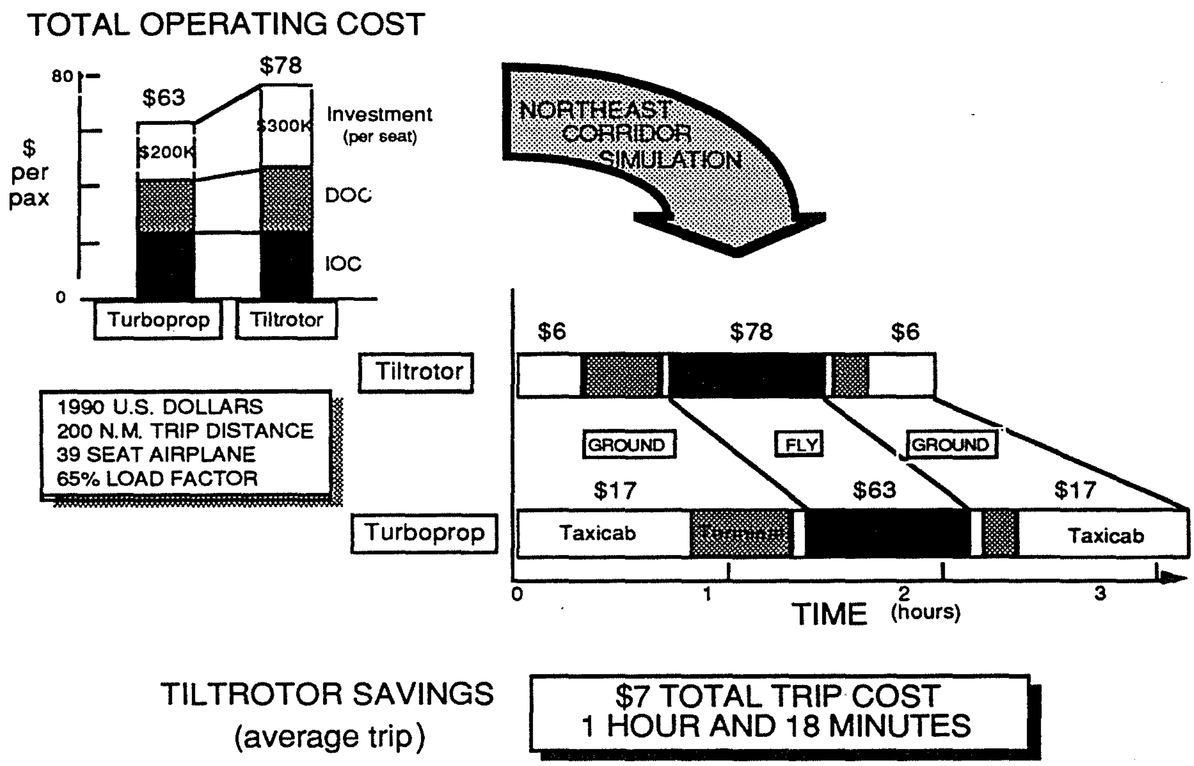


Figure 17. Tiltrotor economic viability - network simulation results

While the cost per seat for the tiltrotor was deliberately somewhat conservative, a doubling of investment cost in the ticket price is clearly unacceptable. While much of the responsibility for high utilization rests with the manufacturer, two research activities may be useful to examine: transmission health monitoring and efficient de-icing systems.

Transmission Health Monitoring

After the rotor system, the transmission is the single biggest difference between turboprops and tiltrotors. The need for higher rpm reduction and the alternating torque loads in helicopter mode are the source of higher weight and maintenance. In addition, the design guidelines must assume the most probable spectrum of greatest loads and duration. There is no such thing as an emergency transmission rating. Inspecting and changing a transmission must be kept to a minimum in scheduled operations. Therefore, a system of monitoring the "health" of the transmission could be quite useful. If it can be certified, such a system could lead to emergency ratings and less over-design for the vast majority of civil missions. Key tasks in this research are development of sensors and the algorithms that determine how fast critical conditions are approaching.

De-icing Systems

There is no commercial aircraft that is truly "all weather." However, scheduled tiltrotor service may have to operate efficiently in some state of continuous icing. This requirement may exceed the V-22 de-icing capability and deserves some investigation. Weight and power are crucial. NASA has pioneered electro-expulsive de-icing systems using various techniques that use little weight or energy. These may be applicable to tiltrotors.

Unique Tiltrotor Design Issues

The NASA High Speed Studies (reference 2 - 5) explored several configuration possibilities not mentioned above. These include canard designs with higher forward wing sweep (Figure 18), active rotor control for inherently unstable conditions, dual speed engines, and integration of flight/propulsion/mode control.

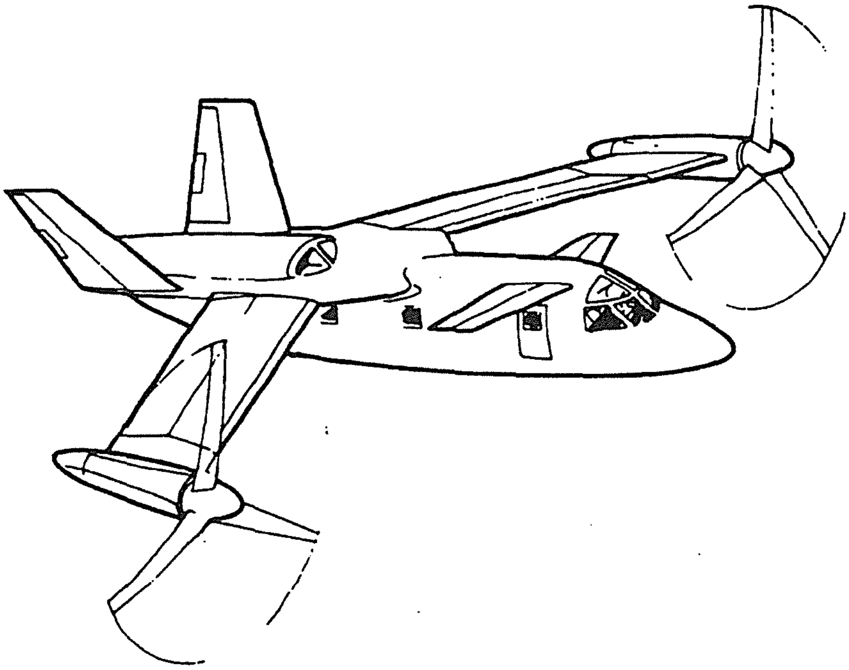


Figure 18. Canard tiltrotor (artist's rendering)

Folding tiltrotor designs were also examined. If these concepts are to be considered for increased research, risk and cost of implementation, especially for certification, must be addressed. It is unlikely that these technologies would see service on the first advanced commercial tiltrotor

International Cooperation

In creating a new form of commercial air transportation, the technical challenges require the best efforts of all affected parties. This includes certification agencies, regional and local government authorities, and the industries that have an economical stake in the outcome. Certainly there are issues that transcend competitive national interests where cooperation could be mutually beneficial. Safety, air traffic control, terminal area criteria and certification are international because aircraft operations are international. Indeed, the Civil Airworthiness Authority of the United Kingdom has participated with NASA and the FAA in joint piloted simulations for civil tiltrotor criteria. But beyond these natural areas for cooperation there are other technology activities where cooperation may be feasible and beneficial.

Conclusion

The NASA research that evolves out of these examinations will provide technology options to U.S. industry to meet the demands of the marketplace and remain competitive. NASA will also work with the FAA to define certification criteria, air and ground infrastructure requirements, and other operational issues. NASA will continue to work with the Department of the Navy, as appropriate, for the technology issues in the development of the V-22 Osprey tiltrotor. The demands upon the NASA budget are many and growing. Increasing funding for tiltrotor research will be a challenge. NASA believes that the tiltrotor has potential for civil application and has research underway to meet some of the technology challenges discussed above, but much work needs to be done.

Disclaimer

The views expressed in this paper are the opinions of the authors and do not represent any official position of NASA, or Boeing Helicopter Division.

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