DOCUMENTED BRIEFING

RAND

Dual-Use Technology Program for a Passenger-Cargo Rotorcraft

David Dreyfuss, Calvin Shipbaugh, Jeff Hagen, Richard Buenneke

Arroyo Center

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Prepared for the United States Army

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Approved for public release; distribution unlimited

PREFACE

This document reports results of a RAND study of potential commercial applications for advanced rotorcraft. The study was sponsored by the Deputy Assistant Secretary for Research and Technology, U.S. Army. The project was conducted in the Force Development and Technology Program of RAND's Arroyo Center, a federally funded research and development center sponsored by the United States Army.

SUMMARY

Motivation for Examining Commercial Rotorcraft Markets

The number of new military acquisition starts is being reduced as a result of declining RDT&E and procurement budgets. The Army needs to consider new ways of doing business that will permit it to get the most from the limited acquisition dollars available. One possibility is to exploit dual-use technology programs. A candidate for Army participation in a dual-use technology program is a joint military/commercial cargo/commuter rotorcraft. There is general interest in whether market sensitivities point to technology areas that can be recommended as inputs to a National Rotorcraft Technology Center. Of particular interest is the identification of any commercial markets that could generate significant demand for a rotorcraft that is similar in size to the CH-47D, which constitutes the latest version of an aging but vital aircraft.

Selecting Representative Case Studies

We examined a spectrum of markets that possibly could employ rotorcraft of various types and sizes; we did not make any *a priori* designation of the rotorcraft type or design to be used. In terms of the parameters that drive each market, we could see characteristics emerge that indicated the type of rotorcraft that might be suitable, e.g., the range of speed or aircraft size needed to allow a profitable operation. The market demand, and likely market size, can be compared with cost to determine if the market is feasible, or if it can be made viable with appropriate technological improvements. The market examples we analyzed were chosen to reflect larger generic market sets and to capture cases that were both analyzable and representative of a reasonably sized market.

Rising costs pose a formidable challenge to rotorcraft operators and users. We have explored three methods as potential solutions to the problem: (1) exploit the unique attributes of rotorcraft, (2) search for factors governing successful niche markets, and (3) address factors that reduce acquisition and operating costs. To explore these three approaches to creating successful conditions for rotorcraft operation, we first addressed the passenger and cargo markets because they are able to exploit the flexibility of rotorcraft. Then we examined the requirements for success in two of the most promising rotorcraft niches: support to offshore oil drilling platforms and emergency medical service (EMS). These are cost sensitive

yet have few competing modes. Finally, we took a direct look at cost factors for specific examples of rotorcraft.

Analysis of Market Characteristics

A rotorcraft that might be suitable for a dual-use approach is one that can service both the high-volume, short-haul commercial aviation market and the military cargo/troop needs of the Army. Such a program could incorporate the best conceptual design technologies developed from the military and commercial requirements. The passenger transportation case is the most obvious example of how a large demand for advanced rotorcraft could emerge. Rotorcraft systems allow flexible takeoff and landing, and they afford relatively easy ground access. Therefore, a well-chosen infrastructure might ease congestion of airports without having to build additional runways or new airports. Infrastructure development might include the adoption of existing locations such as general aviation sites, provided there is initially adequate traffic demand near such sites. Such rotorcraft siting reduces ground travel time, and hence perhaps transportation costs. We examined whether this would create a competitive situation in the California corridor—which is the largest in the nation—for a high-volume, short-haul passenger market.

Due to the large differences in costs, if one assumes that an advanced rotorcraft has comfort, noise, and safety equivalent to a turboprop, we found that only a small fraction of the traffic is expected to be diverted from competing modes, despite these advantages. But if one could enhance the perception of an advanced rotorcraft to be closer to the level of a turbojet, then appreciable traffic will be diverted to the rotorcraft link as the demand increases by a factor in excess of three.

On the basis of cost alone, rotorcraft are not competitive for hauling cargo, and it is not generally profitable to use rotorcraft in head-to-head competition with other modes for cargo transport. However, there is an opportunity for a cargo niche. We examined the evolution of cargo transport as an adjunct to a passenger market. Rotorcraft offer relatively easy access to downtown areas (especially when compared to fixed-wing aircraft) and move at relatively high speeds (especially when compared to trucks).

In examining the niche markets, we found that operations supporting service in the offshore oil market currently use rotorcraft that can and do compete with surface transport, although there is strong dependence on used vehicles. To achieve the same system cost as a typical fleet helicopter, for example, if a new rotorcraft were to cost two times as much per seat, it must then also cruise at 250 knots. System costs are much more

sensitive to operating costs than to the other parameters. Changes of ten cents per seat-mile can mean the difference between success and failure.

Although the offshore oil exploration market for rotorcraft is difficult to predict, there are at least 150 to 250 helicopters in the United States that are used for full-time offshore support and exploration, with perhaps twice as many used worldwide. New exploration is currently under way in Indonesia, Venezuela, Alaska, and other traditional and nontraditional sites, but the probability that any of them will be developed depends on the price of oil. With oil prices remaining flat, exploration and development are restricted to small-scale, one-time efforts that are not adequate to build or sustain a substantial rotorcraft market.

In the EMS market, our study of moving patients between hospitals and to and from accident scenes shows that there are several critical vehicle attributes, or drivers. A cruise speed of 200–250 knots appears to offer the best compromise between staff cost minimization and operating cost reductions. The size of most current EMS vehicles is 8–10 passengers. These can easily transport two patients, which constitute the vast majority of all calls. A 8,000-pound weight limit is set by the maximum disk loading and rotor diameter to allow landings in restricted, unimproved areas such as highway shoulders. The large market for patient transfer missions has the same vehicle characteristics that apply to accident scene rescues. Patient transfer cases call for small numbers of passengers to be transferred over short distances.

A market estimate of 350 vehicles is derived from current fleet sizes and a simple area calculation for the entire continental United States and Alaska assuming a 250-knot vehicle. Different speeds yield different numbers, which in turn affect the amortization of research and development costs. Although fewer higher-speed vehicles would be sold, causing higher unit prices to recoup costs, this cost increase is vastly smaller than the cost savings obtained via medical staff reductions.

Approaches to Reduce Cost

The Army maintains separate procurement and operations budgets, but commercial airline operators include cost of ownership as an operation cost. We adopt this latter categorization in order to analyze procurement decisions for the commercial sector.

The application of "lean" manufacturing or improved product processing might be considered to further reduce rotorcraft production costs. If lean manufacturing could reduce rotorcraft production costs by 30 percent, reflecting the approximate level of gains it has achieved for the Boeing

777, one could expect the cost of ownership and even some insurance costs to drop proportionately. However, ownership costs are only about one-third of all costs, and direct and indirect operations account for the balance.

Advanced rotorcraft designs can provide some savings. Helicopter empty weight can be reduced by almost 40 percent, and fuel consumption can be lowered by almost 45 percent. Expected improvements in tiltrotor designs are not quite as dramatic, but they are expected to lead to a reduction of 25 percent in empty weight and 40 percent in fuel consumption. The exact relationship between weight reduction and the corresponding fractional influence on cost is not linear. For instance, very-low-weight, high-cost composites could drive the relationship in the wrong direction; so technology development along these lines must emphasize methods that constrain the cost of composites or other weight-reducing technologies. We assume an optimistic relationship to examine an upper bound for these particular technology directions.

More generally, a number of high-leverage technologies should be addressed in detail in an attempt to reduce rotorcraft costs and improve acceptance by users. A number of fixed-wing technologies might be captured to improve new rotorcraft. These include materials (composites), improved product process decisions, digital controls (with accompanying software), designing for high-utilization operations, and simulators for pilot and mechanic training. On the other hand, rotorcraft-specific technologies that might be drawn upon include rotor noise reduction, contingency engine ratings (i.e., upgrades for one-engine-inoperative), civil crashworthiness, health and usage monitoring systems (HUMS), integrated high-performance turbine engine technologies (IHPTET), and improved aerodynamics.

Maintenance costs are the single largest contributor to the direct operating costs of today's helicopters. The key to reducing the amount of scheduled maintenance is to move towards performing maintenance only as needed, rather than a schedule fixed by lifetime-limited parts and time between overhauls. Long-lifetime parts and accurate monitoring and diagnostic methods are then required to ensure that safety is not compromised. The use of HUMS could also provide imminent warning of problems to pilots.

Conclusions About Leveraging Commercial Rotorcraft Markets

We explored several approaches to addressing the cost barrier to establishing a commercially driven market for dual-use rotorcraft, and

have found that there is only marginal opportunity to develop markets driven by profitable business operations. None of the market spectrum we explored shows promise for a significant requirement for a medium-heavy rotorcraft that could serve as a CH-47D replacement. The best opportunity to develop large fleets of medium-to-large rotorcraft is found in the short-haul, high-volume passenger market. However, tremendous improvements in perceptions of comfort and safety levels will be needed to ensure sufficient user acceptance to create demand in the presence of competing modes. A cargo niche that takes advantage of an emerging passenger service may be a factor that assists in the development of a rotorcraft market, but on its own the cargo service is not adequate to create a large market.

Some unique markets employing mostly smaller-sized rotorcraft may create either a small demand for new vehicles or a demand for replacement of aging vehicles. Several technologies, such as composites or smart materials, could be applicable to rotorcraft of different sizes. Improvements in a number of technology areas—engines, airframes, rotors, gearbox, and flight controls—might help reduce cost and move markets toward a more favorable outlook. However, caution must be exercised to avoid adding technology that improves performance but also causes a dramatic *increase* in cost.

We cannot recommend dual-use as a clear remedy for the Army's need for a near-term medium-heavy rotorcraft, but we do suggest that several cost-reducing technologies be examined. These include technologies that reduce empty weight, but also important are technologies that more generally affect any new vehicle's operating costs. Comparison of rotorcraft characteristics with Army requirements, beyond the obvious case of vehicle size, will have to fall out of identification of technological trends that clearly reduce cost enough so that a strong commercial market can then be developed. At present there is not yet a case for a shift of rotorcraft development from the military to the commercial sector. But the promise that rotorcraft offer in terms of minimizing the additional investment in infrastructure to gain short-haul capacity should be further analyzed. The observation that the current air transport system involves enormous investment in land and buildings, often assumed by public entities, compared to far lower investments by the airlines, suggests that a study of the tradeoff between rotorcraft performance and infrastructure investment could be worthwhile. An exploration of how these tradeoffs could be accomplished in terms of a promising public/private partnership could be quite useful.

ACKNOWLEDGMENTS

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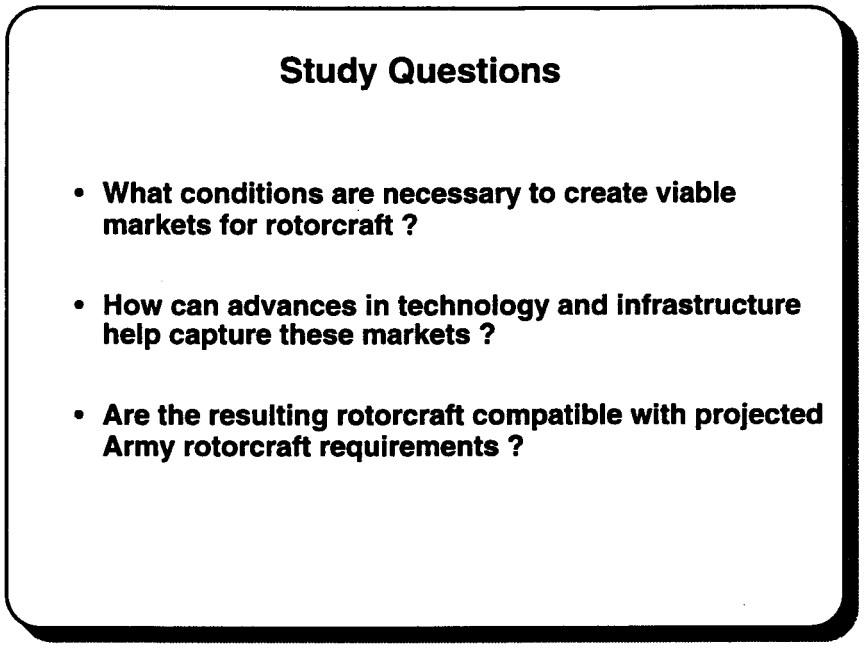
Dual-Use Technology Program for a Passenger–Cargo Rotorcraft

This briefing presents the results of a study sponsored by the Deputy Assistant Secretary for Research and Technology, U.S. Army. The study examined whether a viable commercial rotorcraft market might give rise to dual-use rotorcraft suitable for Army operations. In particular, could a suitable replacement emerge for the aging CH-47?

We define a rotorcraft as any vehicle that depends on propulsive force rather than aerodynamic lift for landing and takeoff. Thus a helicopter, a tiltrotor, or a tiltwing is a rotorcraft, despite significant differences among them in configuration, performance, and maturity of technology. A Harrier VTOL is not a rotorcraft. We note that the infrastructure and markets may be related to specific types of rotorcraft.

The CH-47D can perform a variety of heavy lift functions. Its nominal characteristics are an empty weight of approximately 27,000 pounds, a payload of 18,000 pounds, a range of 500 nautical miles (NM), and the ability to carry approximately 44 combat-equipped troops.



The study addressed three principal questions: What conditions, if any, are necessary to create viable markets for rotorcraft? How can advances in technology and infrastructure help? Are the resulting commercial rotorcraft compatible with projected Army requirements—e.g., a CH-47 replacement?

To understand the extent to which a dual-use approach can be driven by the commercial sector, one must also understand the economic viability of rotorcraft in the commercial aviation market. This study considered the commercial market potential of rotorcraft, the infrastructure implications, and the technology/requirements issues of candidate design concepts. Our foremost emphasis has been on answering the question, "Will significant markets prove profitable for rotorcraft manufacturers, operators, and users, so that a commercially driven dual-use rotorcraft is feasible, and what factors are important in assisting such market development?"

We assume that the distinctions between helicopters and tiltrotors will emerge as part of the market analysis. The principal but not the only difference between the two concepts is speed. The helicopter probably has a maximum speed of 180 knots, while the tiltrotor maximum speed is approximately 260 knots.

Guidance for the Study

- **Examine a wide range of possible rotorcraft markets**
  - **Mass transit**
  - **Short-haul cargo**
  - **Rapid delivery**
  - **Resource exploration and development**
  - **Observation**
  - **Entertainment**
- **Let rotorcraft characteristics emerge from markets**

The study is market oriented. We examined a wide range of markets and concentrated on those where potential existed for sizable fleets of vehicles—i.e., scheduled passenger service, short-haul cargo, emergency medical services, and offshore oil. Several of these markets are currently using large numbers of air vehicles, though not necessarily rotorcraft. Specific rotorcraft characteristics, such as speed, payload, and range, emerged from our analyses.

Rotorcraft Face Stiff Competition in Costs

Passenger cost per available seat mile

	Current estimate
Helicopter	$.50–1.00
Tiltrotor	.40–.50
Turboprop	.22
Southwest Airlines turbojet	.09

Cargo cost per ton-mile

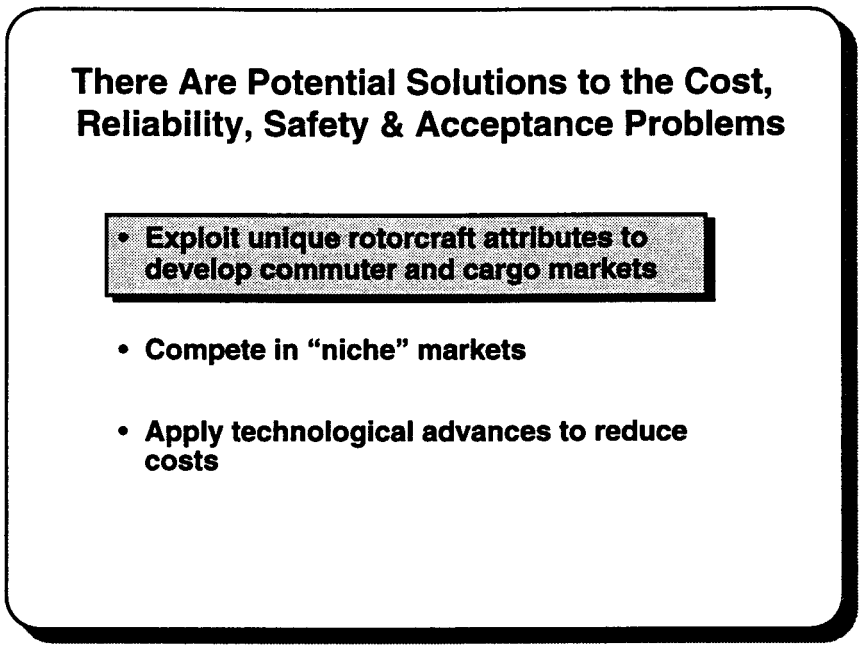
Small passenger helicopter	$6.40
Passenger tiltrotor	3.60
Large cargo helicopter	2.95
Turbojet (U.S. mail)	1.16

Cost is an important though not the only factor affecting rotorcraft acceptance. Cost studies using actual costs of the CH-47D and MD-900 helicopters show current costs per available seat-mile (ASM) of approximately $.85. The range of $0.50–$1.00 reflects an optimistic perception of improved costs as a result of greater scale economies. There is no certainty that these can be achieved. Tiltrotor costs were obtained from the Boeing Phase Two study for "paper," not actual designs, and as such are subject to uncertainty. Turboprop costs are the average of operating costs for five actual vehicles, and the Southwest Airlines turbojet costs are from a *Wall Street Journal* article.

Rotorcraft face a difficult challenge in gaining acceptance by passengers and operators. The virtual absence of any scheduled helicopter carriers in the United States and the dismal history of scheduled service in a number of urban areas has made vertical flight an exotic curiosity for civilian travelers. The recent history of the V-22 tiltrotor is not likely to enhance public and carrier perceptions of rotorcraft. Also, the current focus on the ATR turboprop's problem in the commuter safety area is likely to act as an additional obstacle.

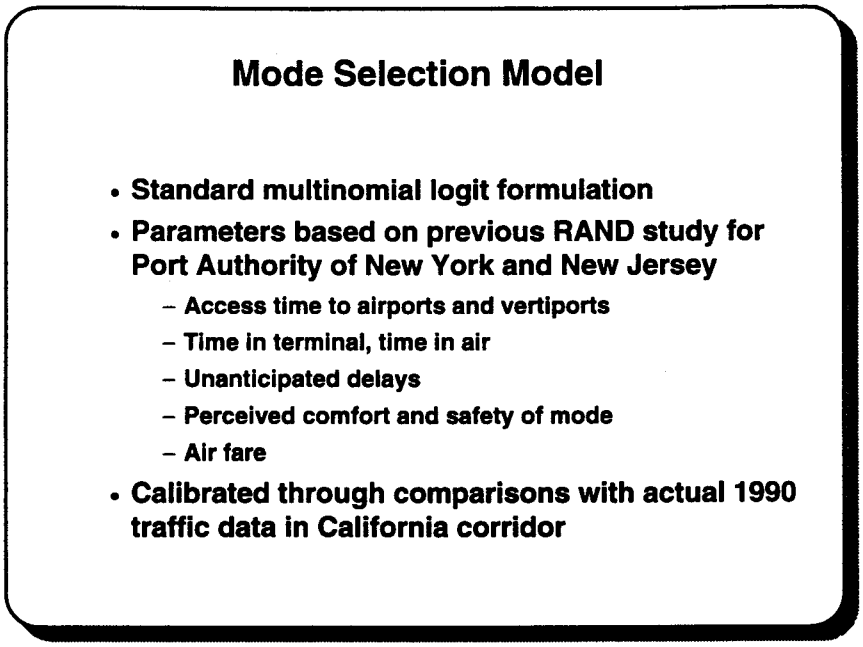
The largest barrier now facing rotorcraft in leveraging new markets or capturing existing market share is their relatively high acquisition and operating costs. Those high costs are due to a simple fact: vehicles that depend on propulsive force weigh and cost more than those that employ aerodynamic lift. This is likely to be true in the future as well. Therefore,

in both the passenger- and cargo-hauling business, rotorcraft are high-cost vehicles. Unless they have compensating attributes, such as easy ground access or faster response time, they will be unable to compete. Even then, issues of safety, noise, reliability, and comfort may prevent significant penetration into the passenger market.



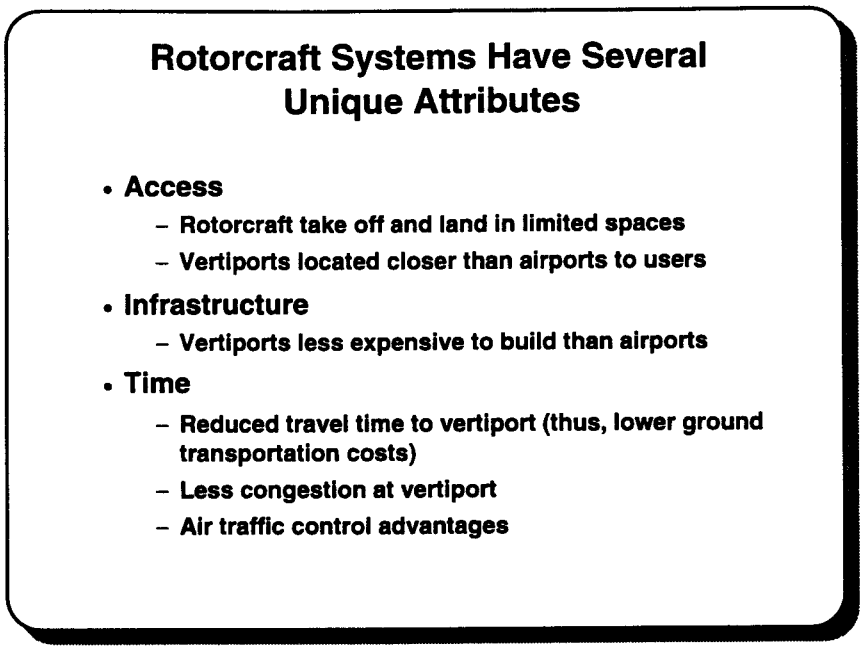
There are at least three potential solutions to these cost disadvantages, each of which will be described in turn. The first relies on the large demand for scheduled short-haul passenger and cargo service; the second explores two mode-limited "niche" markets, emergency medical services and offshore oil services; the third addresses technology issues applied to the cost problem.

However, cost is only one of the problems facing new rotorcraft. Safety, noise, reliability, etc. are also extremely important, particularly as more and more attention is focused on issues of commuter safety in the wake of recent accidents.



The departure point for this portion of the project was the logit mode-choice methodology that had been developed for a previous RAND study. That approach had served an investigation of short-haul, high-volume passenger traffic and could, in principle, be extended to other geographic regions besides the Northeast. However, it was not adequate to handle other regions requiring new database development or to predict drivers for other market types—e.g., an emergent cargo market. Modeling was therefore done on a market-by-market case. This restricted the volume of potential market space that could be explored and led us to select representative market cases that would enable us to understand the different drivers that might be expected to influence future rotorcraft market development.

No "silver-bullet" market niches emerged from our study. In an attempt to model the potential for building a rotorcraft niche by exploiting a market, we investigated a cargo opportunity that depends on a passenger market that achieves at least modest success. We based the methodology for this case on consideration of the time value of cargo and the restraints imposed by time windows.



In serving a passenger and cargo market, rotorcraft have several characteristics that may help offset their cost disadvantage. Vertical landing and takeoff can be accomplished in limited space in or near major metropolitan areas. Moreover, because rotorcraft do not require expensive infrastructure or runways, the cost of building vertiports is much lower than that for large airport facilities (as will be discussed more fully below). Vertiports can also be located more conveniently than large metropolitan airports; therefore, travelers are likely to benefit from a savings in travel time and in cost of ground transportation.

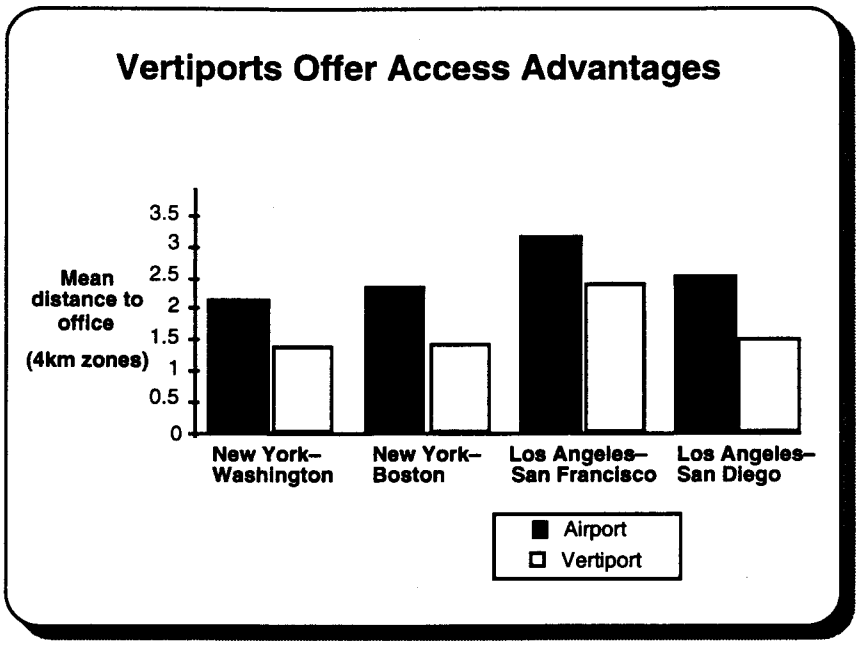
Finally, rotorcraft could offer a more efficient utilization of existing ground and airside infrastructure and capacity at existing airports.

Passenger Distance From Transport Mode Could Play Key Role in Mode Choice

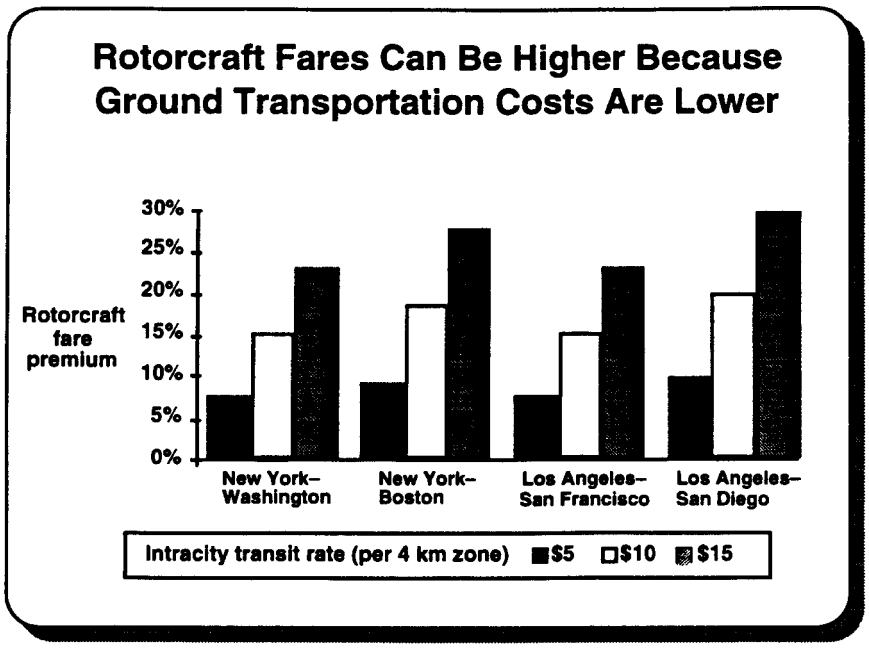
Methodology: Calculate comparative distances to transportation node for four city pairs

- **Locations based on sites identified in regional civil tiltrotor studies**
- **Vertiports sited in or near downtown areas**
- **Other scheduled service available from smaller fields near concentrations of "edge cities"**

Using 4-kilometer grids, we calculated comparative distances to transportation nodes for four city pairs. The sites were based on locations identified in regional tiltrotor studies. Taking the distances in conjunction with office space densities, we generated matrices of weighted distances from offices to each transport mode. We then used these distances in conjunction with costs and times for ground transport to generate potential allowable fare premiums for rotorcraft service.



This chart shows comparative travel distances to airports and vertiports, again using 4-kilometer grids weighted by office space as the basis for the calculation. On average, there is a savings of 5 kilometers to and from the vertiports, which translates into a savings of about 10 kilometers per one-way trip. We note that a kilometer saving in a congested area such as midtown New York or Boston translates into a much greater time saving than a kilometer saving in less-congested markets.



Reduction in distance traveled can translate to a reduction in ground transportation cost. This in turn means that a passenger could be charged a higher rotorcraft ticket price and still pay no more overall than the total package cost (e.g., ground plus air) for an alternative form of transportation.

Depending on what assumptions underlie the calculation for ground transportation, the ticket price premium could be as high as 30 percent. This premium is based only on ground transportation savings at both ends of a one-way trip.

Intercity Rotorcraft Demand

Case study analysis of California corridor

- **Larger than East Coast, Great Lakes markets**
- **Many "Edge Cities" removed from airports**

Mode choice model used to predict rotorcraft market share

- **Based on surveys of passengers**
- **Choices influenced by relative utilities of jet, rotorcraft modes**

Utility a function of:

- **Time savings**
- **Fare savings**
- **Passenger "small aircraft aversion"**

The approach adopted to determine the potential market demand for intercity travel by advanced rotorcraft is based on a two-step analysis.

The first step consists of a review of demand projections from previous tiltrotor studies, with the two goals of identifying promising markets and the demand projection methodology used. On the basis of this review, we modified the demand analysis approach used in the previous RAND tiltrotor study (Aroesty, Rubenson, and Gosling, 1991) to address the objectives of the current study.

The second step consists of a detailed analysis of a case study corridor, in order to understand how the market demand for rotorcraft service is influenced by such factors as aircraft size and costs, and alternative vertiport configurations. This analysis provides a basis for understanding the tradeoffs involved in the design of both the rotorcraft and the associated system of vertiports. Since the competitive advantage of rotorcraft for intercity transportation lies in their ability to offer service from locations that are closer to the traveler's origins or destinations, it follows that this access advantage must be large enough to offset any higher costs and differences in flight time and service frequency, compared to alternative services.

What is needed from a ridership perspective is a large number of vertiports in a region, offering frequent service at competitive cost levels. However, while smaller aircraft allow more frequent service at a given load factor, they tend to have higher unit costs, due to fixed cost

components. Thus tradeoffs exist between aircraft size, service frequency, and number of vertiports.

For the purposes of the current study, it was decided to perform the case-study analysis on the California corridor between the San Francisco Bay Area and Southern California. Previous studies concluded that high-speed rotorcraft (tiltrotors) could not capture a significant market share for downtown-to-downtown service in the Northeast corridor (Aroesty, Rubenson, and Gosling, 1991) or in the Chicago-Detroit corridor (SH&E Inc., 1992). Earlier studies ruled out rotorcraft for shorter-range, intraurban travel (Lu et al., 1972).

Because urban areas east of the Mississippi are relatively compact, the access advantages offered by rotorcraft may not be as significant as they are in more sprawling metropolitan regions in the West. In the West, the central business district may actually be smaller than outlying concentrations of offices in "Edge Cities" scattered throughout the region (Garreau, 1991). And although distances between cities are greater, compared to the East, the shorter travel times to suburban vertiports may cut total travel time.

The corridor analysis models the diversion of trips from existing air services to rotorcraft service, under alternative scenarios addressing the tradeoffs discussed above, as well as different fare levels reflecting differences in the cost of developing and operating the system.

The California corridor between the Bay Area and Southern California links two metropolitan areas with a combined population of about 20 million in 1990. The Bay Area is served by three commercial service airports with flights to five Southern California airports. There are small numbers of commercial flights at other airports in the two regions, but they are mostly intraregional feeder flights and do not serve the corridor. In 1990, the three Bay Area airports—San Francisco International (SFO), Oakland (OAK), and San Jose (SJC)—each had service to five Southern California airports—Los Angeles International (LAX), Burbank (BUR), Orange County (SNA), Ontario (ONT), and Long Beach (LGB).

In 1990, the average daily corridor traffic was about 11,600 passengers each way. The route between San Francisco International and Los Angeles International carried the largest share of corridor traffic.

Model Structure

The four key variables that define any given scenario are the location of the vertiports, the flight frequencies between them, the fares offered, and

the size (and associated cost characteristics) of the aircraft used. For a given rotorcraft technology, it is assumed that a commercial operator would optimize the other variables to maximize the profit. But the inherent difficulty of rotorcraft passenger operations over longer hauls must be recognized. Thus, it may not be feasible to capture market share for the LA–SF route.

The definition of the vertiport system determines the number of vertiports between which service is provided and the vertiport access times involved. The flight frequencies, fares, and access times determine the traffic demand that is attracted to the rotorcraft system; the number of vertiports between which service is provided and the flight frequencies determine the cost of providing the service, for a given rotorcraft technology. Similarly, the traffic demand attracted to each link of the system and the corresponding fares determine the total revenue, and hence the profit (or loss).

It should be noted that model structure provides one other output: the average load factor on each link. While this can vary over a wide range, there is a practical upper limit. If a given combination of model input values generates a load factor that is unreasonably high, then that is not a valid scenario, and the fare should be increased to reduce the demand.

In order to analyze the number of air passengers who would be attracted to a rotorcraft service in the corridor, we developed an intercity demand allocation model, based on prior work addressing airport choice in multi-airport regions. The model uses an approach similar to that adopted by the Boeing Mode Split Simulation (BMOSS) model, which was used in studies for NASA of the potential demand for tiltrotor aircraft (Hopperstad, 1993).

In both models, alternative modes and routes are represented as separate links between terminals in each region, such as airports and vertiports. Travelers choose between alternative links, based on the access time to reach the terminal at the start of the link from their trip origin and to reach their final destination from the terminal at the end of the link, as well as the service characteristics of each link, such as frequency and fare.

The model analyzes a sample of travel parties that reflect the composition of the traffic in the market, in terms of trip origins and destinations, as well as such characteristics as party size, trip purpose, and income, and it allocates the parties to each link using a link choice model.

Each party is assigned a weight factor that converts the resulting link flows to an average daily traffic on the link. This weight factor can also be used to correct for any bias in the sample of travel parties.

Development of the Air Passenger Database

In order to apply the demand allocation model, it is necessary to have a passenger database of information on the pattern of trip making in the market being analyzed. This database must obviously include all the variables required by the model, including trip origin and destination, travel party size, household income, and so forth.

The database for the corridor analysis in the current study was assembled from air passenger surveys conducted at airports in the Bay Area in August 1990 by the Metropolitan Transportation Commission and in Southern California in 1987 by the Los Angeles Department of Airports and Burbank Airport. The surveys did not include the actual trip end in the destination region, only the destination airport. In addition, the Southern California surveys did not cover all airports in the region (only Los Angeles International, Ontario, and Burbank) and did not obtain respondent income data.

Therefore, it was necessary to merge the information from the different surveys to generate a suitable passenger database. This was based on air party characteristics from the Bay Area survey, since it was more detailed and provided consistent coverage of travel to all five Southern California airports.

Southern California trip ends for each air party were assigned on the basis of the trip end distributions obtained from the Southern California surveys, controlling for such factors as trip purpose and whether the respondent was a Bay Area resident or Southern California resident. Actual survey data were used for Burbank, Los Angeles International, and Ontario airports. In the case of Long Beach and John Wayne (Orange County) airports, for which survey data were not available, we developed a trip generation model to allocate the airport traffic to analysis zones. Using the data from the other three airports, we estimated a simple demand allocation model for analysis zones that generated few trips to Long Beach and John Wayne airports. We used this model to estimate the trips to these two airports, based on the trips from each zone to the three airports for which data were available. Finally, these trip estimates were adjusted to give the correct airport totals.

Link Choice Process

The model is based on a link choice process. In this process, a typical travel party is going from an origin zone in one metropolitan region to a destination zone in the other. Each party has a choice of four possible intercity routes:

1. Conventional air service from an airport serving the origin region to an airport in the destination region.
2. Rotorcraft service from a vertiport in the origin region to the airport serving the destination region.
3. Rotorcraft service from the airport in the origin region to a vertiport serving the destination region.
4. An alternative rotorcraft service from the vertiport in the origin region to another vertiport in the destination region.

In each case, the party will have to travel by the regional surface transportation system from the origin zone to the terminal at the start of the intercity link, and from the terminal at the other end of the link to the destination zone.

In other regions, high-speed rail travel might provide a fourth travel option. Because no high-speed service is planned for the California corridor in the foreseeable future, this analysis considers only fixed-wing and rotorcraft links.

Link Choice Model

The link choice model incorporated in the Intercity Demand Allocation (IDEA) model in the current study is based on a multinominal logistic regression formulation. This type of choice model has been widely used for intercity mode and route choice analysis.

The form of the utility function follows the one used in the previous RAND tiltrotor study for the Port Authority of New York and New Jersey, with the following variables:

- Highway travel time to access the airports/vertiports from the origin zone and to reach the destination zone.
- Scheduled flight time and time spent in the airport/vertiport terminal.
- Inconvenience due to flight schedules not matching desired travel times (schedule delay), measured as the average headway over the day.
- Airfare.

The inclusion of terminal time in the utility function reflects the expectation that travelers will need to allow less time for terminal processing and waiting at smaller vertiports than at large airports,

representing a net saving of travel time. This term could also be used to reflect differences in flight time (actual or perceived) due to different levels of air traffic delay between a rotorcraft service and conventional air service.

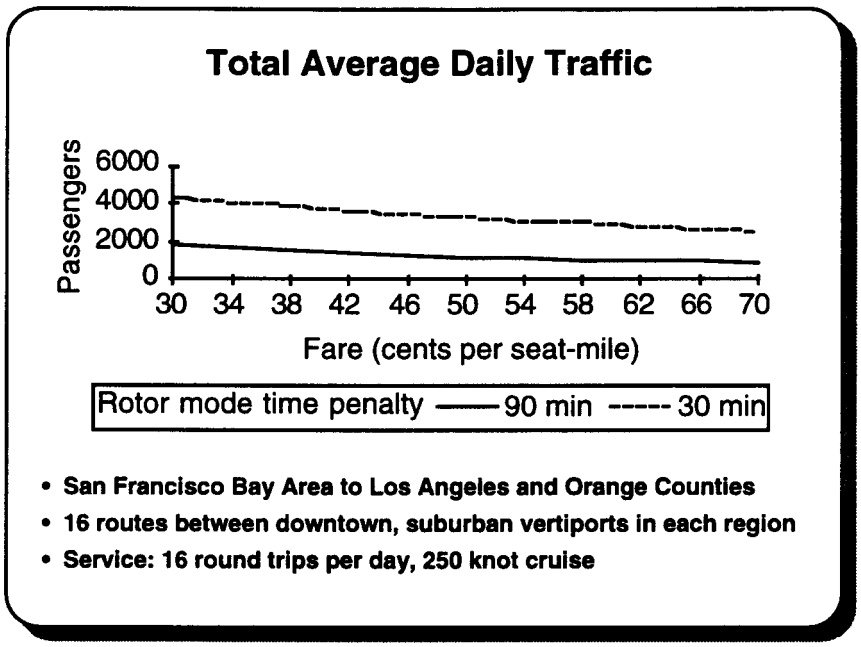
The airfare variable used in the model is the average yield (i.e., net of taxes), for consistency with data on existing services as well as revenue calculations. For the current study, it was assumed that fixed-wing fares and frequencies would be the same as in 1990.

Rotorcraft and fixed-wing carriers were assumed to offer only a single fare to all customers. No fare discounts were offered for restricted round trips to improve overall revenue.

It also was assumed that fixed-wing carriers would not respond to the introduction of rotorcraft service by initiating a "fare war" competition to maintain market share.

Most parameter values were obtained by calibrating the choice model on the California corridor dataset. Another parameter, the rotorcraft mode-specific constant, is derived from research on passenger preferences for jet aircraft over smaller turboprop aircraft (Kanafani and Ghobrial, 1985, and MacNeil, 1985). This "small plane aversion" can be interpreted as meaning that a passenger would be indifferent between a longer travel time flying on a turboprop compared to flying on a rotorcraft. But the additional disutility of the rotorcraft service over identical jet service is represented as a time penalty.

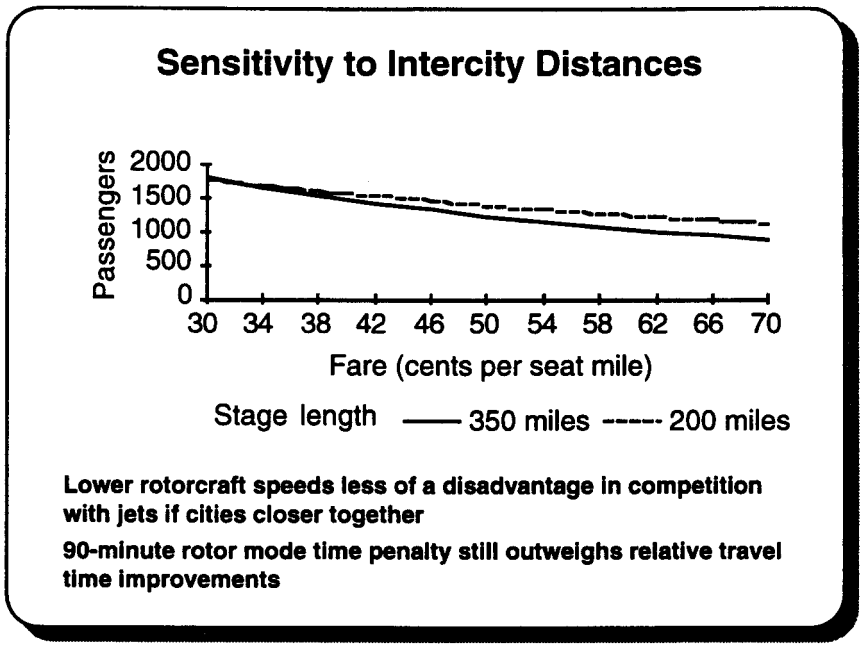
In our modeling, we evaluated passenger mode choices with a rotorcraft mode-specific time penalty of 90 minutes—a constant equal to the estimated time penalty for turboprops. We also considered mode choices with more "jet-like" rotorcraft competing against jet service. These vehicles have a time penalty of only 30 minutes. We emphasize that the data are limited to assign specific time penalties for rotorcraft or even turboprops compared to jet transports, and that our use of this variable is a quantitative attempt to reflect passenger acceptance of the technology.



In our analysis, we evaluated four system configurations. A given system configuration specifies the number and location of the vertiports as well as the service links between them. It also specifies the fares and frequencies of competing intercity services. The four configurations are:

1. A single route between downtown vertiports at the China Basin in San Francisco and Los Angeles Union Station.
2. Multiple routes between China Basin and multiple vertiports in the Los Angeles region. The vertiports included Union Station as well as facilities at Fullerton, Van Nuys, and Santa Monica municipal airports.
3. Multiple routes between Union Station and the San Francisco region. Bay Area vertiports included China Basin, Oakland Army Base, Concord Buchanan Field, and Petaluma Municipal Airport.
4. Multiple routes between four sites in the Bay Area (China Basin, Oakland Army Base, Concord Buchanan, and Petaluma) and four sites in the Los Angeles region (Union Station, Fullerton, Van Nuys, and Santa Monica). A total of 16 two-way routes were flown between these locations.

The chart above shows total average daily traffic for the fourth configuration. If the "small aircraft aversion" for rotorcraft is comparable to that for turboprops, rotorcraft will not capture a significant market share at the fare levels required to cover operating costs. If turboprops can be made more "jet-like," market share might be large enough to permit a viable service. Conversely, passenger aversion to rotorcraft could be even greater than for turboprops.



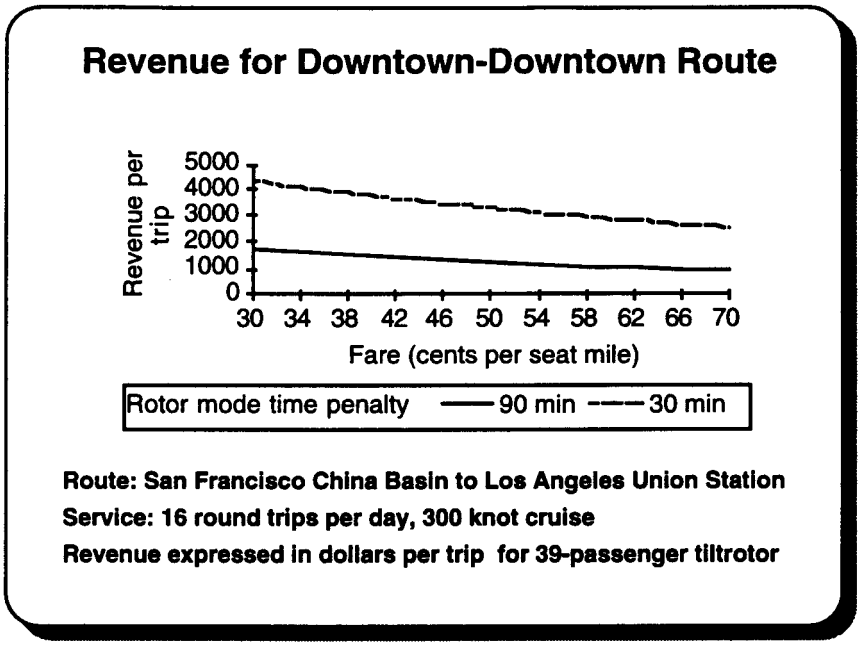
Compared with major cities in the Northeast corridor, the San Francisco Bay and Los Angeles regions are separated by a greater distance. Measured in air miles, the distance between the central cities of Los Angeles and San Francisco is 350 miles. By comparison, the distance between New York and Boston is 190 miles and the distance between New York and Washington is 200 miles.

Because jets have higher cruising speeds than rotorcraft, they have a relatively shorter block time for flights between more distant city pairs. Over long distances, this advantage overwhelms any time savings offered by easier access to vertiports.

However, the speed advantage of jets is less significant between less-distant city pairs. Between these city pairs, rotorcraft should receive a larger share of total traffic.

The chart above illustrates how a shorter intercity distance—modeled by shortening the distance of each route by 150 miles—increases average daily traffic. However, this increase is fairly modest.

Because this model only considers flight times in California, it does not account for the delays imposed by the greater air traffic congestion in the Northeast corridor. This congestion also might improve the relative position of all-weather rotorcraft operating outside of congested fixed-wing flight routes. However, the sensitivity analysis shown above suggests that these improvements would probably still be outweighed by the dominant "small plane aversion" factor.



Rotorcraft service in California would have much higher ticket prices than competing jet services. One-way ticket prices would range from $104 to $243 for the 345-mile (300 nautical mile) route between China Basin and Union Station. By comparison, the unrestricted fare for jet shuttle service between Los Angeles and San Francisco international airports is $104 (in 1990 dollars).

In addition to higher ticket prices, rotorcraft would face a "small plane aversion." If this is comparable to the aversion faced by turboprops, load factors would be too low for profitable service. The chart above shows estimates of revenue yield in terms of cents per available seat-mile. This figure is a function of the load factor of the aircraft (the percentage of seats occupied) and fare charged to passengers.

If rotorcraft are perceived as comparable to turbojets, load factors would be less than 27 percent of a 39-passenger vehicle at fares of 30 cents per mile (or a ticket price of $104) for a service providing 16 flights per day. Load factors drop to less than 12 percent at fares of 70 cents per mile ($243 per ticket). The most revenue possible on this route is available at 46 cents per mile ($146 per ticket).

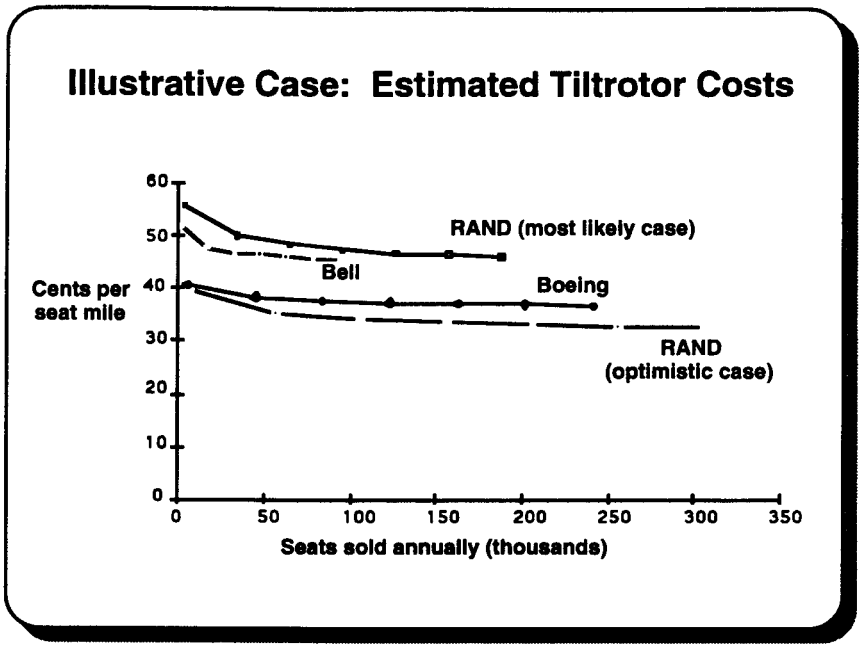
However, the load factor is only 19 percent, resulting in an average total revenue of $1,181 per trip. To break even on this service with a 39-passenger rotorcraft, operating costs can be no more than 8.77 cents per available seat-mile. Since these cost levels are less than a fourth of the most optimistic cost

projections for an advanced rotorcraft, no commercial service would be viable with rotorcraft acceptance comparable to turboprops.

If a rotorcraft could provide a more "jet-like" service, a rotorcraft operator could charge much higher fares. With a rotorcraft mode-specific penalty of 30 minutes, revenue would be maximized at fares of 70 cents per mile. At this fare, the load factor would be 46 percent for a 39-passenger vehicle. To break even, operating costs would have to be less than 32 cents per available seat-mile.

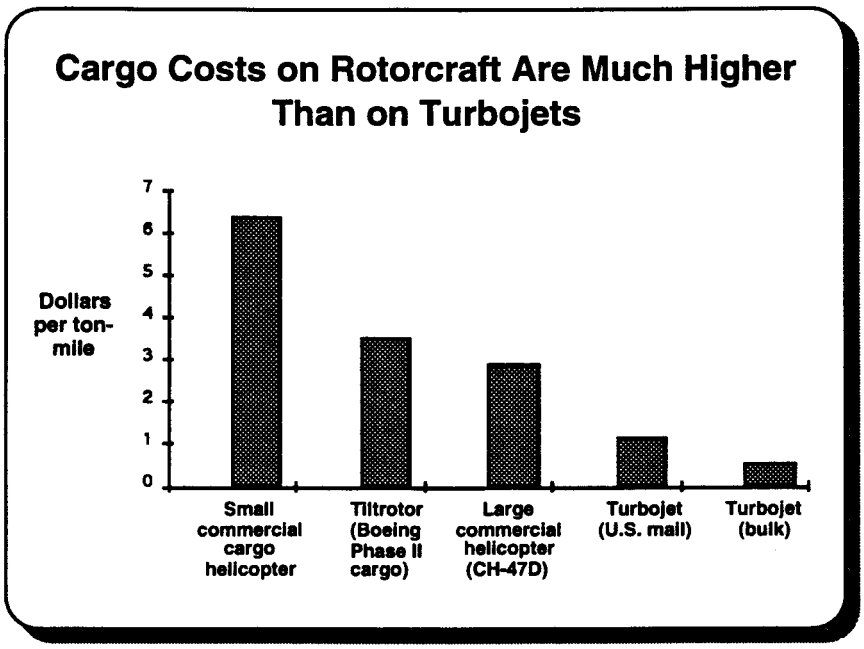
These operating costs do not include landing fees or other infrastructure costs. Because all but the Union Station and China Basin nodes are based at existing airfields, costs would be less than for a whole network of new vertiports. However, access to these facilities also might be contingent on operators using "fly friendly" measures to minimize repeated flights on the same approach pattern. Such measures have helped win community acceptance for Helijet Airways, the only scheduled rotorcraft passenger service in North America (Glaze, 1993).

Although service might not be economical with a 39-passenger vehicle, a smaller rotorcraft might be able to operate profitably. But the analysis underscores the importance of passenger (and ultimately carrier) acceptance of rotorcraft as an attractive means of traversing longer distances.



The chart shows the supply side of the picture, in a range of possible costs. The vertical axis here should be used in comparison with the horizontal axes of the previous charts. Two contractor estimates, Boeing's 1991 Phase II and Bell's, are illustrated along with two RAND estimates, the first based on a very optimistic set of assumptions and the second based on a more likely and conservative set. Boeing has recently completed a Phase III study, with even lower figures than RAND's optimistic case. The results above are reasonably consistent, but none of them allows for expected cost growth, nor does any one cover amortization of RDT&E expenditures.

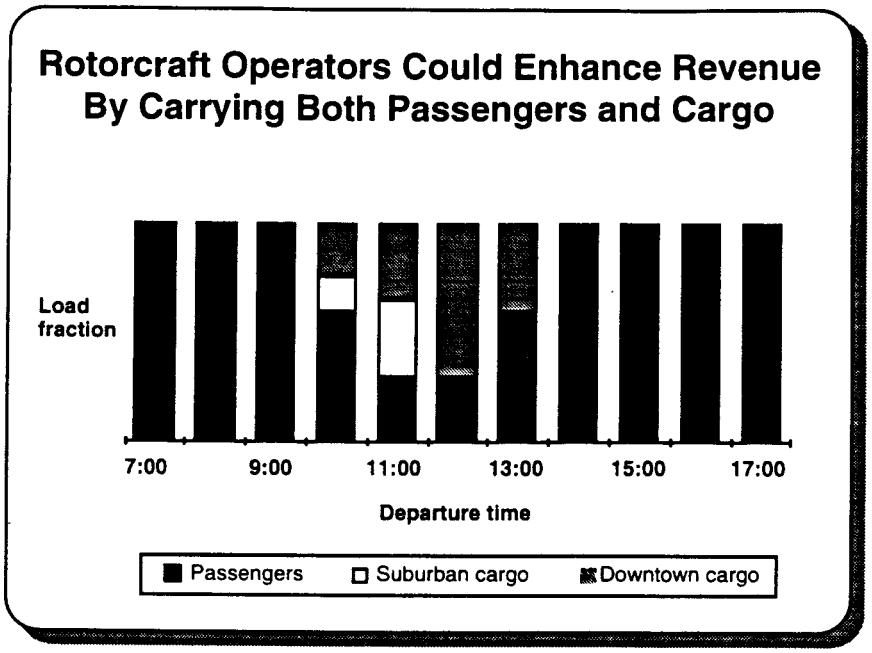
The V-22 has had substantial cost growth in its development program. But we have no actual operational costs for that vehicle, as it is still in its flight test phase, and we don't know whether the V-22 flight experience is reflected in the new Boeing estimates.



In examining how advanced rotorcraft might be used for cargo service, it is important to consider the unique attributes of vertiflight vehicles. They offer relatively easy access to downtown areas (especially when compared to fixed-wing aircraft) and move at relatively high speeds (especially when compared to trucks).

For a commercial cargo service to succeed, the economic value of these advantages must exceed the higher ton-mile transport costs associated with vertiflight. Both U.S. mail and bulk cargo carriers are much lower in cost than are the rotorcraft. However, neither of them offers same-day delivery, as is proposed for rotorcraft operations. This criterion led us to reject a detailed analysis of next-day cargo service. In all cases, the ground and fixed-wing modes used by Federal Express and other overnight services can fulfill a midmorning delivery guarantee at a lower cost than could be achieved by a rotorcraft competitor. As a result, these services would quickly drive any vertiflight-based service out of business.

Our analysis did not consider the use of advanced rotorcraft for "as soon as possible" (ASAP) deliveries of critical business materials. Rotorcraft delivery of time-critical items is undoubtedly a valuable service. For crucial parts, senders would be willing to pay very high prices for ASAP service. Unfortunately, the demand for such service is difficult to forecast in terms of both time and location. Thus, it is difficult to envision a scheduled operation that would be profitable. The demand for ASAP parts deliveries might be best met by charters or by a service similar to a network for emergency medical service (EMS) transport.



This notional chart shows how a midday service could improve the utilization of rotorcraft resources while maintaining a high frequency of flights. During the morning, rotorcraft would provide dedicated passenger service. After arriving at their destinations, vehicles would be reconfigured for dual passenger–cargo service.

At midday there is a lull in the passenger loading factor that could be compensated for by quick roll-on, roll-off cargo for same-day delivery of high-value items. To increase load factors, late-morning flights might start from suburban "edge cities" and then transit through vertiports in the central city. Flights in the early afternoon would travel directly between central cities. After reaching their destinations in the midafternoon, vehicles would again be reconfigured for all-passenger service during the late afternoon. We concluded that this scenario is only marginally cost-effective and is strongly challenged by competing cargo delivery modes. If rotorcraft are to become a viable competitor for same-day cargo service, a dual-use rotorcraft research and development program must reduce pound-mile costs to no more than 10 to 30 percent above costs for fixed-wing aircraft with comparable range.

Infrastructure for Vertiports Is Less Expensive Than That for Airports

- **Estimated cost of Denver airport: $3.4 billion***
- **Estimated cost of one vertiport: $0.5 billion in a nonprime downtown or suburban area**
- **Rate of construction: Every five years, postpone one airport and build two vertiports**
- **Net infrastructure savings: $670 million annually**
  - **$3.4 billion minus $1 billion = $2.4 billion every five years**
  - **$480 million per year plus interest (8% per year = $190 million annually)**

* *Wall Street Journal*, August 5, 1994.

Another potential for expansion of rotorcraft service could lead to savings in the infrastructure of the national airport system. As space in metropolitan areas becomes more expensive and more scarce, the cost of building new airports or adding runways to existing ones can be expected to skyrocket. Rotorcraft use vertiports, which are vertical landing and takeoff facilities. Vertiports do not require runways; therefore, they can be much smaller and be located much closer to downtown areas. It is estimated that commuter flights account for approximately 40 percent of all landings and takeoffs and carry about 26 percent of the passengers nationwide. The potential for savings in airport use comes from substitution of rotorcraft flights for fixed-wing commuter flights, thus lessening the demand for airport runways and slots.

In our estimates, we assumed that a large vertiport in a downtown area could be built for less than $0.5 billion, including land, parking facilities, gates, pads and tarmac, main buildings, rental car facilities, baggage handling equipment, intermodal interfaces, and air traffic control and communications facilities. Of course, if rotorcraft could use existing, convenient regional airports, then the cost savings would be even greater, although the time-saved benefits may not be as great. These trades are clearly location specific.

Dallas indicates that its vertiport will cost $300 million; however, we took the price of Los Angeles and San Francisco real estate into account in preparing our estimate. The new Denver airport is expected to cost $3.4 to

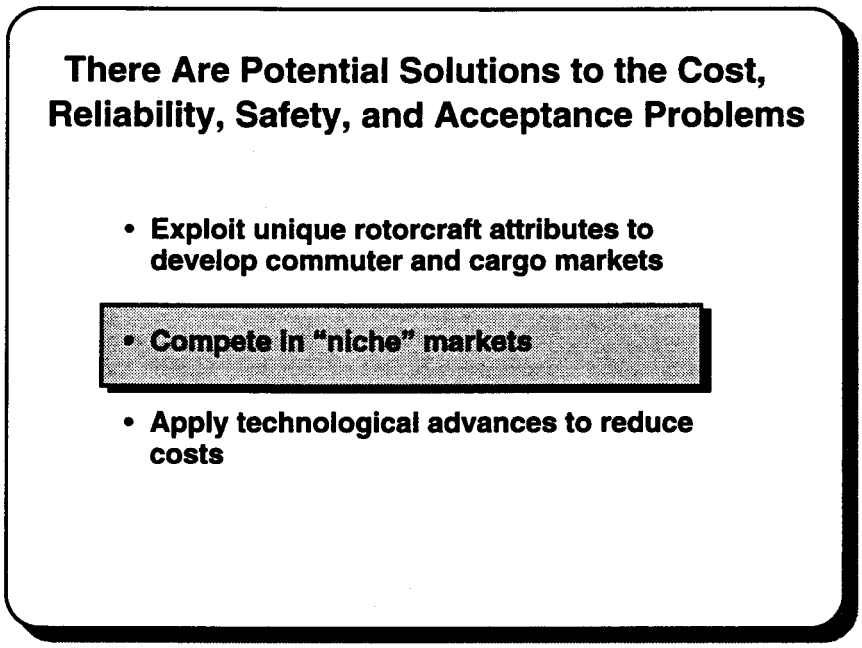
$3.7 billion. Therefore, if the DIA can be forgone at the cost of two vertiports, then the annual savings would be $670 million. These funds are not fungible and they could not be used for the development of the rotorcraft, but they do represent savings to the nation's air transportation system. The issue of community acceptance of new vertiports is not easy to resolve, although some near-downtown sites can be envisioned that would pose fewer problems. Also, passengers would need to change their travel patterns and be more receptive to departing from an office rather than home.

Passenger and Cargo Markets: Observations

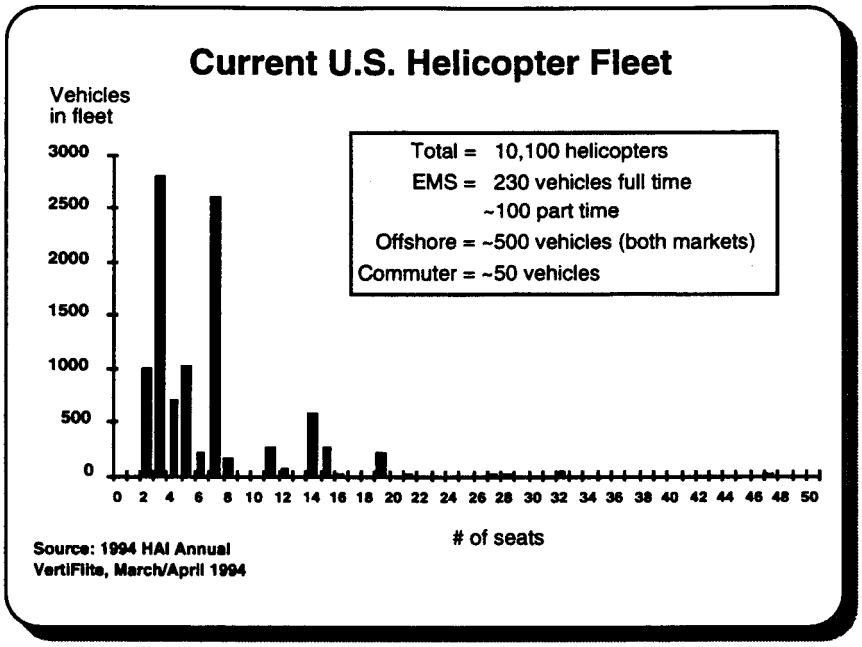
- **Passenger market**
  - Supply and demand are marginally convergent with 70 percent load factors but do not provide any margin for expected cost growth
  - Passenger and community acceptance of rotorcraft comfort, noise, and safety must meet or exceed that of turboprops
- **Cargo market**
  - Not economically viable as a stand-alone operation but may be a revenue enhancer for off-peak hours
  - Requires rotorcraft designs to be rapidly convertible from passenger-only to passenger–cargo configurations

The short-haul scheduled passenger market, now dominated by turboprop aircraft, is the market that rotorcraft would have to compete in. This competition could not be based on price, since rotorcraft cannot bring their costs down to turboprop costs, but would have to be based on convenience and time savings. The critical factor is the level of passenger aversion. Shown previously as 30- and 90-minute time penalties, rotorcraft need to achieve aversion factors that are *much* better than those for turboprops. It is difficult to envision how this could be achieved, given the intrinsic qualities of the rotorcraft as a commercial means of transporting passengers.

If a passenger configuration is built, based on the California corridor passenger demand, the optimum size is about 40 passengers. The same-day short-haul cargo market for rotorcraft is not viable as a stand-alone operation but could be used as a revenue enhancer for the passenger market in off-peak hours. However, it requires a rotorcraft that is rapidly convertible to a passenger-cargo configuration.



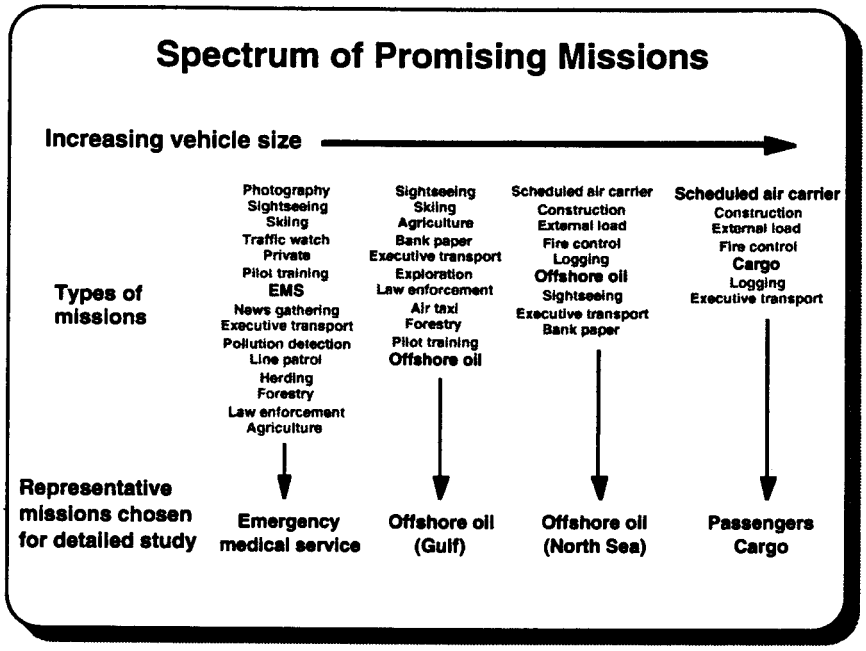
The second potential solution to the disadvantages of rotorcraft is to compete in smaller, more specialized markets, which for the most part are dominated today by helicopters.



This chart displays a sample of the U.S. civilian helicopter fleet as of December 1993. The total of approximately 10,100 vehicles is displayed as a function of total seats per vehicle. As can be seen, fully 50 percent of the U.S. fleet consists of helicopters with four or fewer seats. These vehicles are typically used for utility and patrol missions such as crop spraying, line patrol, and pilot training. The Army helicopter most in need of replacement, the 47-seat CH-47, has a total of 13 helicopters of equivalent size in the U.S. civilian fleet. Although there are current and planned competitors in this size class, such as the EH-101, civilian sales have been few and far between. The current market demand for this class of rotorcraft is evidently very small.

The total fleet numbers can also be broken down into mission categories. The accuracy of these numbers is poor, however, due to the practice of helicopter operators maximizing the utility of their vehicles by varying their activities. A 7-seat Bell 206L may ferry a load to an offshore platform in the morning and perform a construction job in the afternoon. With this caveat in mind, rough estimates of the number of rotorcraft used in a variety of missions can be made. With around 500 vehicles, the largest number fall into the offshore category; the smallest category, with a tenth as many vehicles, is commuter. This commuter category does not include air taxi and charter missions, only those in somewhat regularly scheduled passenger operations. There are two distinct types of operators captured here: a few airport-based shuttle operations, and previously existent helicopter operators setting up a commuter service to serve a short-term,

demand-based need such as those formed in the aftermath of the 1993 Los Angeles earthquake. Regularly scheduled helicopter service has had a varied history, with many starts and subsequent failures. Part of the problem is certainly the sensitivity of passengers to well-publicized and spectacular accidents, such as the one in New York at the Pan Am building some years ago, or the accident that resulted in the failure of L.A. Airways. The small number of vehicles seen here is evidence of the difficulty of helicopter passenger operations.



To simplify the analysis and direct it toward more detailed factors, we divided these typical and potential rotorcraft missions into four categories. We used several criteria, the primary one being vehicle size. Within each category, we selected a single representative mission that offered good potential for development and was amenable to analytical techniques.

As seen in the previous figure, small vehicles, usually known as "utility" size, have the largest market share. In this category, we chose the emergency medical service (EMS) mission. We selected two offshore oil exploration missions for our examination of vehicles that carry 15 to 30 passengers. The largest vehicles, with 40–50 passengers, have already been examined in the cargo/passenger analysis. This size of rotorcraft, which numbers only in the tens of vehicles in the civilian world, is practical for regularly scheduled passenger service, cargo transportation, and a few utility missions such as logging and fire-fighting. Unfortunately, from the Army's current perspective, the CH-47 replacement would likely fall into this category.

Why Might New Rotorcraft Succeed in the Offshore Oil Market?

- Operating costs may be lower and reliability may be higher than for current air vehicles
- Higher speeds can reduce costs by minimizing crew pay and systemwide fleet size
- New low-cost technology may permit safe one-pilot, all-weather operations
- Rotorcraft would have one-engine-inoperative capability for flight safety over water
- Currently, high percentage of aging rotorcraft in this market

Oil rigs and platforms located offshore require constant servicing with manpower, supplies, and parts. Currently, transportation is done via ship and air modes, the choice being governed by expediency, cost, and required payload. Very large items that can be scheduled are delivered by ship, and vital smaller items are transported by air to minimize downtime.

We examined an intermediate case—the transportation of oil workers from shore base to offshore platform. We chose two oil exploration areas: the oil fields in the Gulf of Mexico out of the Galveston port, and the U.K. sector of the North Sea oil fields. These two regions were considered representative of the larger operations around the world. Moreover, they present sufficiently demanding cases for a new rotorcraft, and there is a wealth of data available on operations there.

These regions are extremely challenging to transportation services. Rigs in the Gulf of Mexico are located approximately 80 nautical miles from shore. They enjoy relatively benign weather and are generally sized to be supported by about 15 crew members. The helipads on such rigs have typically been constructed to support 10,000-pound vehicles. In the North Sea, rigs are sized much larger and are subjected to sea and weather conditions much worse than in the Gulf. They are also further offshore—150 nautical miles on average in the U.K. sector.

Several approaches based on high-technology insertion could be considered to design and operate a new rotorcraft with a more competitive profit margin. One is to simply maintain performance but

invest R&D dollars into lowering the operating costs to lower system costs, and also to attempt to lower acquisition costs to increase rate of return on investment. Another approach is to match the cost of current helicopters but increase their speeds to the conceived limit of approximately 180 knots—e.g., through new technology. A third potentially effective solution is to move to a totally new rotorcraft design, such as a compound helicopter or tiltrotor. However, there are operating and acquisition cost ceilings identified that must be met to assure financial acceptance. If the advantage of a new rotorcraft is based on its ability to carry crews more quickly than current modes, it must be recognized that such a vehicle would be susceptible to shrinking crew sizes resulting from automation. Hence its advantage would likewise shrink. Unless oil rigs and platforms move further offshore or require larger payloads, the latest generation of helicopters is not range restricted. Safety considerations tend to keep the size of rotorcraft small, although a few large aircraft may be needed for some cargo. The size of rigs that are actually used in an oil field is a limit on rotorcraft size and is more restrictive in the Gulf of Mexico example than in the North Sea.

Analytic Assumptions for the Offshore Oil Mission

- **Trip cost = $rig crew + $operating costs + $acquisition costs**

  (Operating costs defined as pilot salary, fuel, parts and labor for maintenance, insurance, depreciation)

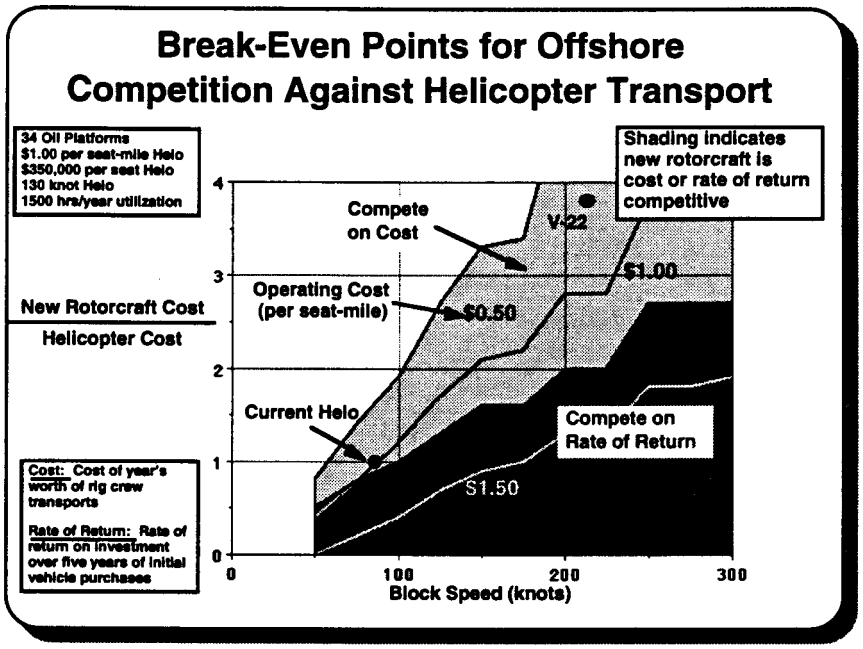
- **Current offshore helicopter users will not transport more than 1/2 rig complement at a time because of safety and insurance concerns**

- **New rotorcraft is "paper" aircraft; variables examined parametrically**

To calculate system costs, we summed the rig crew labor costs, the vehicle operating costs, and the amortized acquisition price. Crews must put in a full shift onboard the rig, and so must be paid overtime while in transit. In our informal survey of several operators, we determined that an average pay scale is approximately $68 an hour for a crew of four plus time and a half overtime; a full Gulf crew of 16 would be paid $408 an hour while transiting.

However, our survey also revealed that, because of safety concerns resulting from several well-publicized accidents in which an entire rig crew was lost, operators will only transport at most half the crew of a given rig at one time. This restriction can be circumvented by carrying partial crews for several closely situated platforms. However, considering insurance restrictions and the need to transport cargo on the same vehicle, carrying half a crew at a time is the most common. Nevertheless, cargo and emergency requirements imply a vehicle large enough to transport an entire crew—16 passengers in the Gulf of Mexico and 30 in the North Sea. The main restriction on the size of vehicles used in the Gulf is helipad weight and size limitations.

For our parametric examination, we chose four variables available to vehicle designers: operating cost, acquisition cost, speed, and yearly utilization. Acquisition cost is a function of the number of vehicles sold, and utilization is also very strongly affected by the operators. However, each of these factors can be influenced by design compromises. Other factors—e.g., range and payload—are determined by rig location and size.



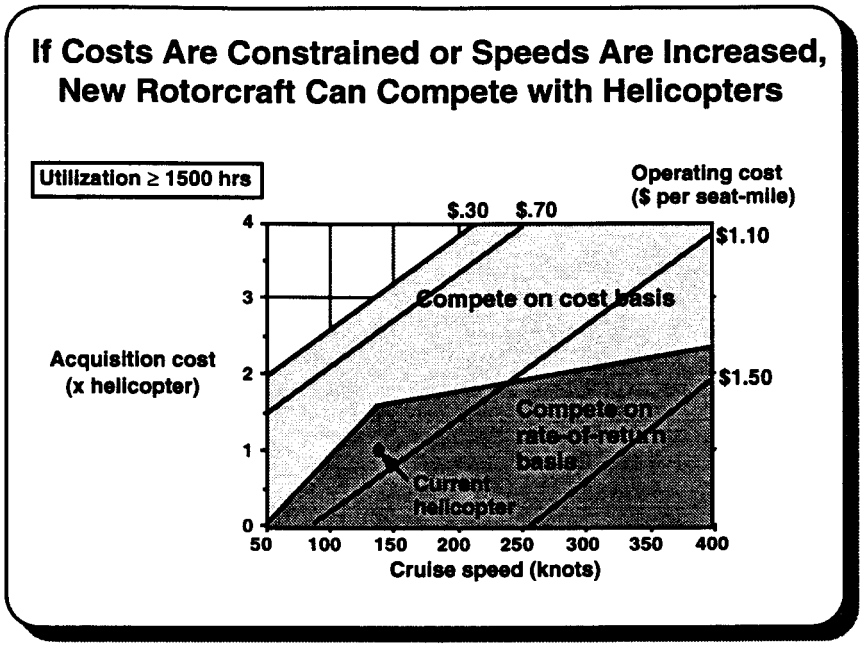
Using a model developed to track system costs, this figure summarizes the results of comparing a new rotorcraft with helicopter transportation. Three variables are shown—speed, acquisition cost, and operating cost—with utilization of the new rotorcraft fixed at 1,500 hours per year. The average utilization in the industry is around 500 hours, but with technology insertions giving reduced maintenance downtime and fewer weather cancellations, in conjunction with the scheduled nature of this service, the higher utilization rate is justified and probably achievable.

As can be seen, the ability of the new rotorcraft to compete on a cost basis is highly dependent on acquisition cost, and at the lower end, on speed. The lighter-shaded regions and lines indicate variable combinations for the new rotorcraft which yield a lower total system cost, compared to helicopter transportation. The current helicopter used for comparison is also shown, based on speed and acquisition cost. The area of this region changes with operating cost; the outer edge of the envelope shown here is for $0.50 per seat-mile. Operating costs greater than this will shrink the region, and smaller costs will expand it.

There is a quite sizable design space in which a new rotorcraft can compete with current air transportation. With current technology, speeds of 250 knots at two to three times the acquisition price of a helicopter and operating costs around $1.00 per seat-mile are probably quite achievable. However, acquisition or operating costs much above this level will make a new rotorcraft financially unviable.

Another way to examine the economics of a new vehicle is the rate of return on investment. This measure evaluates the rate of return received, over ten years in this case, treating the acquisition cost as monies invested. For this study, revenues were assumed to be the same for both transportation modes, and the total system cost was subtracted from it. This measure is much more sensitive to acquisition cost than simply tabulating the overall system cost. Since the investor (whether it is the government or a consortium of private companies) has a choice of vehicles to invest in, the one with the highest rate of return makes the most fiscal sense. A vehicle that offers investors a higher rate of return will be the one purchased, and if it is also cheaper to operate, it will capture market share as well.

The rate-of-return area of competitiveness, shown as the darker-shaded region, shows results similar to those of cost. Since this figure is less sensitive to operating cost than the per-trip cost measure of merit, only the $1.00 per seat-mile region is shown. As shown, within technically achievable limits, there is a large area of possible competitiveness for an offshore system of new rotorcraft. The measures were computed against ship transportation as well, with even better results for a new vehicle. However, the utilization of 1,500 hours/year is an important factor in these analyses.



Once again summarizing results, here against helicopter modes, the general regions of competitiveness are shaded for both cost and rate of return on investment measures of merit. The new rotorcraft and helicopter modes are relatively close in terms of cost, and operating cost is the largest driver. Thus, several different operating cost regions are depicted. Because rate of return is less sensitive to that parameter, an average-sized region is shown. Utilization is also fixed as greater than or equal to 1,500 hours per year.

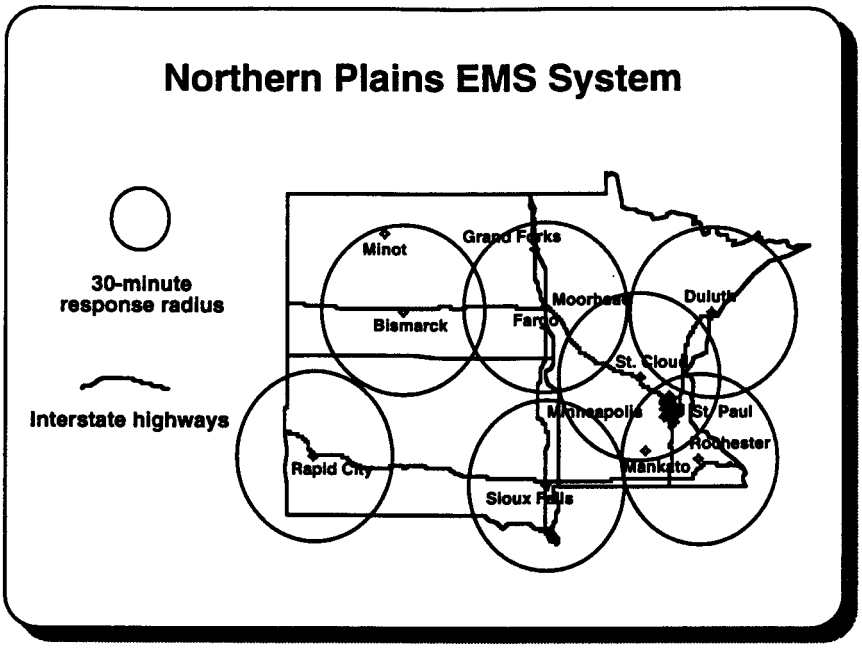
Changes in operating cost create substantial differences in the range of acceptable acquisition prices and vehicle speeds. For example, for a 250-knot vehicle costing twice as much as a helicopter to achieve better rates of return and lower costs, it must have operating costs less than $1.10 per seat-mile. If acquisition price jumps to three times the helicopter price, operating costs must drop to about $0.80 per seat-mile, and there will be difficulty in ever achieving better rates of return on investment.

Why Might Rotorcraft Succeed in the Emergency Medical Service (EMS) Market?

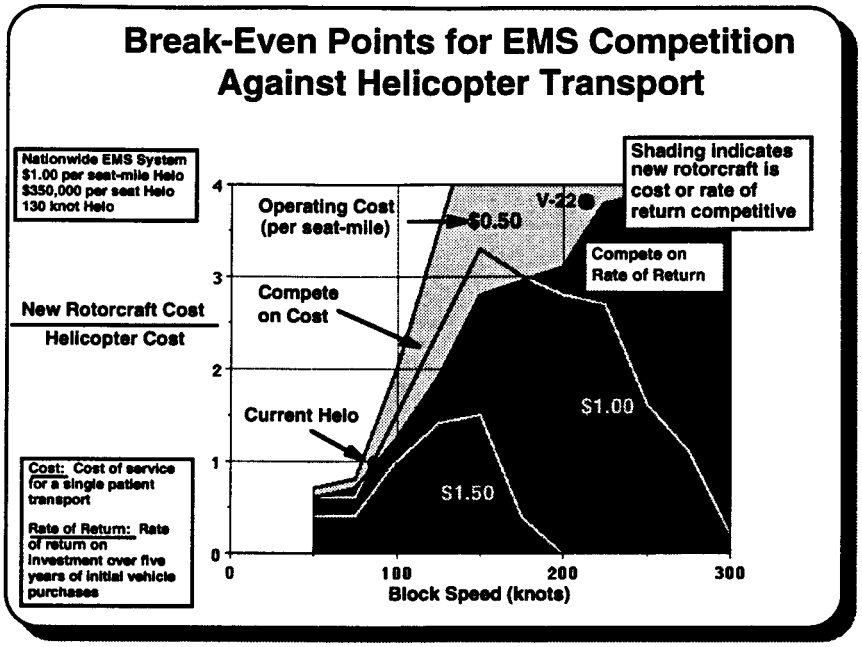
- Mortality is directly related to time span between injury/illness and hospital care: "Golden Hour"
- Current trend is toward consolidation of trauma centers
  - Basing EMS vehicles at or near hospitals saves staffing costs
  - Faster, longer-ranged vehicles will be required to maintain low mortality rates
- New rotorcraft would be ideal fit in current system of ground ambulances and helicopters
  - Replace vehicles traveling more than 30 minutes to emergency
  - Provide access to currently unserved remote areas

The current emergency medical service transport originated out of the recognition that mortality is directly related to the time span between injury and care. During the Korean and Vietnam wars, helicopter evacuation to mobile hospitals was first used to great effect. Although such vehicles provided minimal patient care during transport, quick transport to the trauma facility led to a large decrease in mortality over that of previous conflicts. Today, many urban areas have some type of system with ground and air transportation providing immediate access to a local health care facility. In addition, the helicopters that arrive at the scene of an accident today are practically a hospital-level trauma care unit, lacking only laboratory and surgical facilities, thus providing a higher level of care in a shorter period of time than was ever possible before. Helicopters also play a vital role with ground ambulances and turboprops in interhospital transportation in order to obtain higher levels of care for relatively stable patients. In fact, approximately 60 percent of EMS missions fall into this less time-urgent category.

Although urban areas are well and efficiently covered by ground ambulances, several trends may affect EMS care outside of major city centers. A reduction in the number and a collapse of the locations of trauma care facilities, desire on the part of overburdened insurers to minimize all possible costs, and increasing ground congestion all may play a role in providing a niche for a new EMS vehicle. Rather than being limited to providing quick response for city dwellers, a regional system must offer rapid response and transport to every citizen. The goal of this analysis is to examine what type of vehicle would be most economical in meeting this requirement.



This is a notional layout for a system of 21 300-knot rotorcraft in the Northern Plains region. This analysis is based on providing sufficient numbers of vehicles to cover the region with response times comparable to those seen in cities. The number of vehicles required is a direct function of their speed. This Northern Plains case is interesting due to the very low population density found in this region. For suitable response rates, there are three vehicles at every basing station. They could be evenly distributed around the region, but it would likely be cheaper and more efficient to save on basing costs by simply having three vehicles at each station. Note that such a system has sufficient capacity to provide excellent emergency response as well as to provide interhospital transfer services.

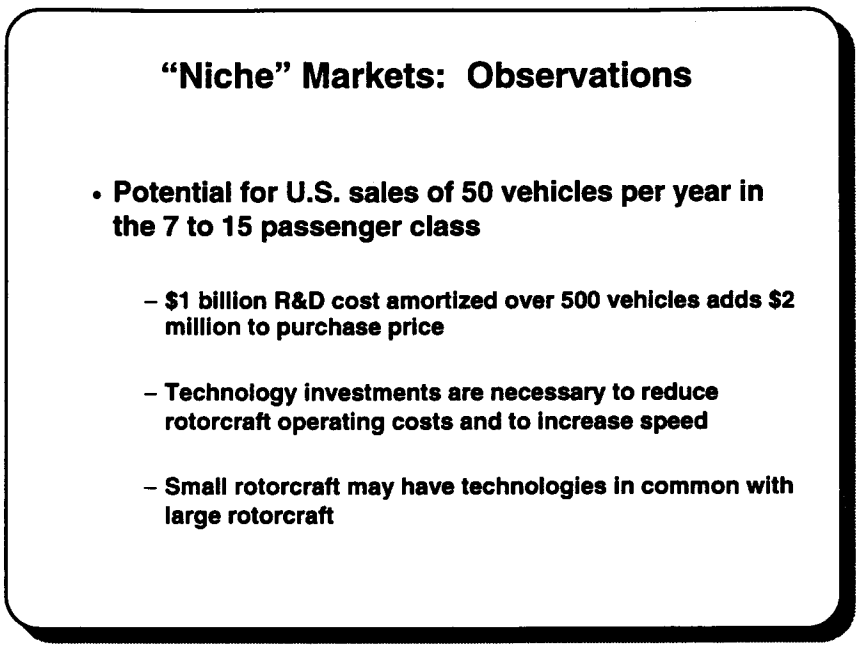


This chart shows regions of cost and rate-of-return benefit for a new rotorcraft in comparison with helicopter EMS transportation. The regions shown are for a variety of operating costs, and utilization is set by number of calls responded to, within the limits of vehicle downtime. The slower vehicles are penalized the most due to the addition of more vehicles to cover the service area, and hence more medical staff to man them. The fastest vehicles will reach a point of diminishing returns due to their long flights leading to large operating costs, which also causes a higher operating cost to have a greater effect on the fastest vehicles.

Competition with currently available helicopters is possible on both cost and rate-of-return measures. Since the differences are smaller, operating cost plays an important role here as well. This chart shows cost-competitive vehicles at three operating costs, and the rate of return, which is relatively less sensitive to operating cost. As can be seen, a 250-knot vehicle faces an acquisition cost ceiling at approximately three times helicopter prices and $1.00 per seat-mile operating costs. Reductions in seat-mile costs help greatly with reducing system costs, but are weaker in assisting with rate of return on investment.

Similar results were seen versus ground ambulances, although the region of competitive rate of return on investment for new rotorcraft is much smaller in this case. This is due to the much smaller unit price of the ground ambulance, despite the larger number of ambulances needed. This price advantage is mostly offset, however, by the need for receiving

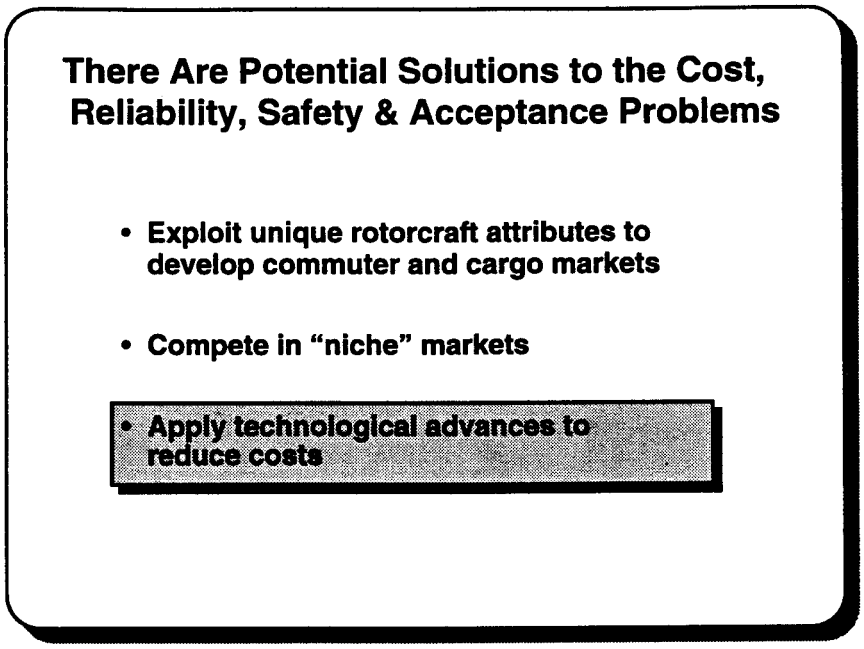
hospitals. With a system of many ground ambulances, there will be enough to pick patients up, but no close facilities to receive them. If the cost of additional hospitals is included in the rate-of-return calculation, air vehicles appear much more attractive.



Several concluding points can be drawn from the results of these two analyses. Applying advanced technology to any one or a combination of rotorcraft attributes can grant substantial cost savings to operators. The most obvious technology advance is speed increase, but new manufacturing techniques, higher-reliability engines, lower structural weight, and more efficient aerodynamics can all contribute to lowering the operating and acquisition costs of rotorcraft. Most current market research indicates that operators cannot afford the helicopters now offered on the market. Only by realizing this, and by intelligently applying technology, can manufacturers reverse this trend. Operators need vehicles that cost less to buy and operate with minimal downtime and maintenance.

Estimates for developing a new rotorcraft are on the order of $1 billion. With a total potential U.S. market of 500 vehicles in the 10 to 15 passenger class, this requires $2 million per vehicle simply to recoup development costs. With an equivalent helicopter currently costing $3.5 to $6 million, this amounts to a significant cost increase. As seen in the preceding results, such a cost increase, although not insignificant, is perhaps manageable, for example if accompanied by reasonable operating costs and high speeds.

Although there is potential for new vehicles to offer higher rates of return on investment than current helicopters do, if these vehicles were new configurations, operator acceptance could be a problem, especially operators made cautious by a market as risky as the one they are currently involved in. Inroads may best be made through military use, government subsidies, and demonstration programs.

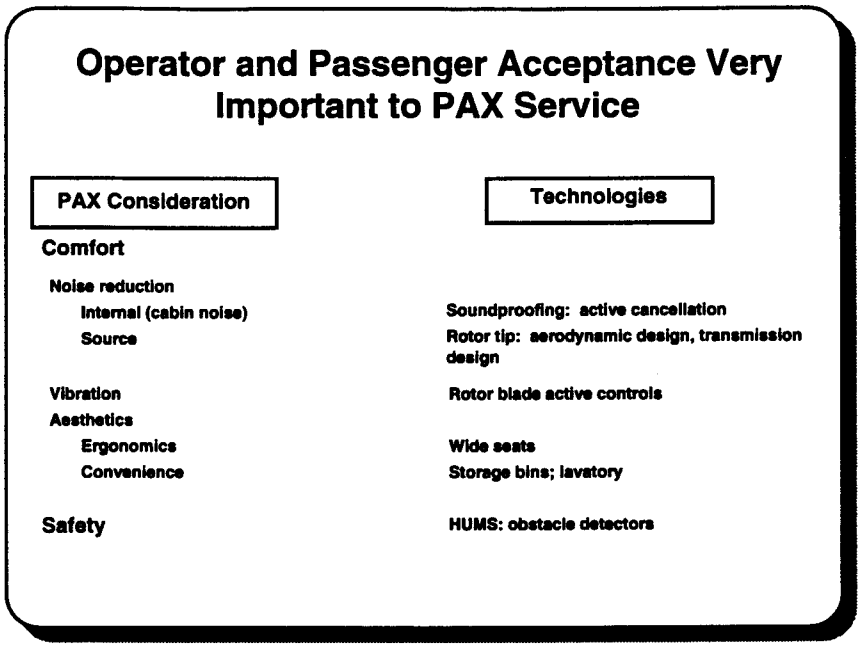


The final means examined for reducing rotorcraft costs for competitive purposes relies on technology to reduce acquisition and ownership costs, increase passenger acceptance and aircraft utilization, and increase performance.

Our Cost Analysis Addressed a Range of Parameters

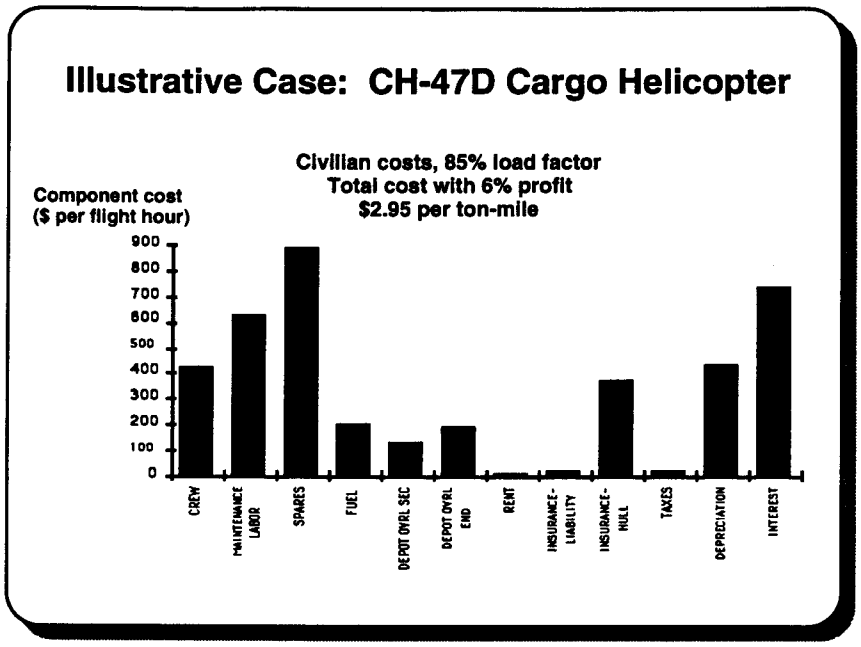
- **Purchase price**
- **Aircraft lifetime**
- **Number of seats**
- **Load factor**
- **Stage length**
- **Speed**
- **Number of trips per day**
- **Number of hours per day of flight time**

We studied the eight parameters listed in this chart, along with several others of less importance. The purpose of this sensitivity analysis was to look for parameters that have high leverages relative to cost. Those are the ones on which attention was concentrated in the technology studies discussed below. It is interesting to note that the operating parameters had more sensitivity than did the ownership parameters. For scheduled passenger service, block time (which is the total trip time, including landing and takeoff delays as well as en-route delays) is the parameter that is often used as a measure of efficiency. In our study, the elapsed time of each mission is the stage length divided by average speed. Average block times could be significantly greater.



The logit demand model reflects acceptance using a mode-specific constant that has an extremely strong influence on the viability of a scheduled passenger rotorcraft service for the general population. This includes perceptions of both comfort and safety. Comfort has several strong components: noise, vibration, and aesthetic/ergonomic considerations. The latter should not be overlooked, given passenger attitudes/concerns that surfaced during focus groups conducted during the earlier RAND study.

Efforts to control the impact of noise on passengers should address reducing both the source of noise and abating the noise leakage into the passenger space. The former can benefit to some extent from soundproofing, and may require active cancellation or headsets. Noise reduction will require focusing on the rotor and fuselage vortex interactions, and might benefit either from better aerodynamic design or from transmissions that work efficiently to allow lower tip speeds. The latter will also aid in community acceptance by lowering external noise. Although this is not a factor in our demand model, it will be a strong factor if a distributed vertiport infrastructure is to be realized. In combination with steep-gradient takeoff and landing, noise objections might be mitigated, but this has to be balanced with passenger acceptance. Vibration is related to the noise problem, and can benefit from smart or adaptive rotor blade control.



In order to determine the areas in which technology insertion would have the highest payoff, we analyzed component costs for three current and potential rotorcraft: the CH-47D, the MD-900, and the Boeing tiltrotor. There was surprising consistency among the three with respect to which categories of costs were highest.

Results for the Army's CH-47D are shown here. The five highest-cost components are maintenance, spares, flight crew, depreciation, and interest. These are the areas in which cost reductions would make any new rotorcraft more competitive.

Fixed-wing large cargo aircraft have higher cost per flying hour but much lower cost per ton-mile because of their greater capacities and speeds. For example, the C-5B has a cruise speed of 570 knots, a 100 percent cargo capacity of 130 tons, and a cost per flying hour of $13,000. If we add another 30 percent for ownership costs, the civilianized cost per flying hour is $17,000. This translates into a cost of $.23 per ton-mile. A more realistic value would be to use an 85 percent load factor, which yields a cost of $.27 per ton-mile, either of which is much lower, as would be expected, than the helicopter.

Advanced Technologies for Rotorcraft Designs

- **Engine: Increase engine-power-to-weight ratio, and reduce SFC per DoD's IHPTET Phase II program goals**
- **Airframe: Reduce weight through greater use of advanced composite materials**
- **Rotors: Improve airfoils and obtain optimum twist to reduce required solidity**
- **Gear box: Reduce weight through split-torque design and use of advanced components**
- **Flight controls: Reduce weight by using fly-by-wire and higher-pressure hydraulic systems**

The rotorcraft examined to date do not compete well with turboprop commuter aircraft on short hauls or with small turbojet aircraft on intermediate-range flights. We therefore asked the Advanced Systems Research and Analysis Office (ASRAO) to forecast advanced rotorcraft designs for the years 2005–2010. These designs are aimed at reducing the empty weight per pound of payload and lowering the fuel weight per pound of payload.

Though the designs are preliminary, they indicate that there is reason to expect technological advances to lead to reductions in the size—and thus most likely the cost—of these vehicles. However, rotorcraft will still *not* be competitive with fixed-wing aircraft. Additionally, these new designs must also be more reliable than the older vehicles to attract a new class of operators into the market.

Effect of Advanced Technology on Rotorcraft Design

	Helicopter		Tiltrotor	
	Baseline	Advanced technology	Baseline	Advanced technology
Empty weight per lb of payload	3.98	2.54	4.10	3.06
Fuel weight per lb of payload	1.22	0.66	0.76	0.44

Reference: ASRAO conceptual design studies

Assuming a 40-passenger vehicle capable of flying 400-mile missions, conceptual design studies with advanced technologies show that with a reasonable set of improvements, helicopter empty weight can be reduced by almost 40 percent and fuel consumption lowered by almost 45 percent. Expected improvements in tiltrotor designs are not quite as dramatic, due to their higher inherent efficiency, but they are expected to lead to a reduction of 25 percent in empty weight and 40 percent in fuel consumption. The V-22 program has not matured in its flight test program as yet to enable us to use actual flight experience to evaluate the effects of tiltrotor versus helicopter.

Effect of Advanced Technology on Rotorcraft Operating Costs

Cost per available seat-mile

	Helicopter		Tiltrotor	
	Baseline	Advanced technology	Baseline	Advanced technology
Rotorcraft cost	$.50	$.35	$.40	$.32
Turboprop cost	$.22	$.18	$.22	$.18
Ratio (rotorcraft/ turboprop)	2.3	1.9	1.9	1.8

Using the advanced designs, we calculated operating costs per available seat-mile. Compared to turboprops (which we also credited with improvements), the new helicopters move from an unfavorable cost ratio of 2.33 to a better, but still uncompelling, ratio of 1.91. With advanced technology, tiltrotors can expect to achieve a ratio of 1.75. The baseline costs for the helicopters and tiltrotors are the lowest current costs, which in fact are quite optimistic. Therefore, these are most likely the best ratios for the helicopters and tiltrotors, and the chances are that they could be poorer than shown.

Rotorcraft Face Stiff Competition in Costs

Passenger cost per available seat mile

	Current estimate	*With technological advances*
Helicopter	$.50–1.00	$.35
Tiltrotor	.40–.50	.32
Turboprop	.22	.18
Southwest Airlines turbojet	.09	.08

Cargo cost per ton-mile

Small passenger helicopter	$6.40	$5.00
Passenger tiltrotor	3.60	2.90
Large cargo helicopter	2.95	2.35
Turbojet (U.S. mail)	1.16	1.00

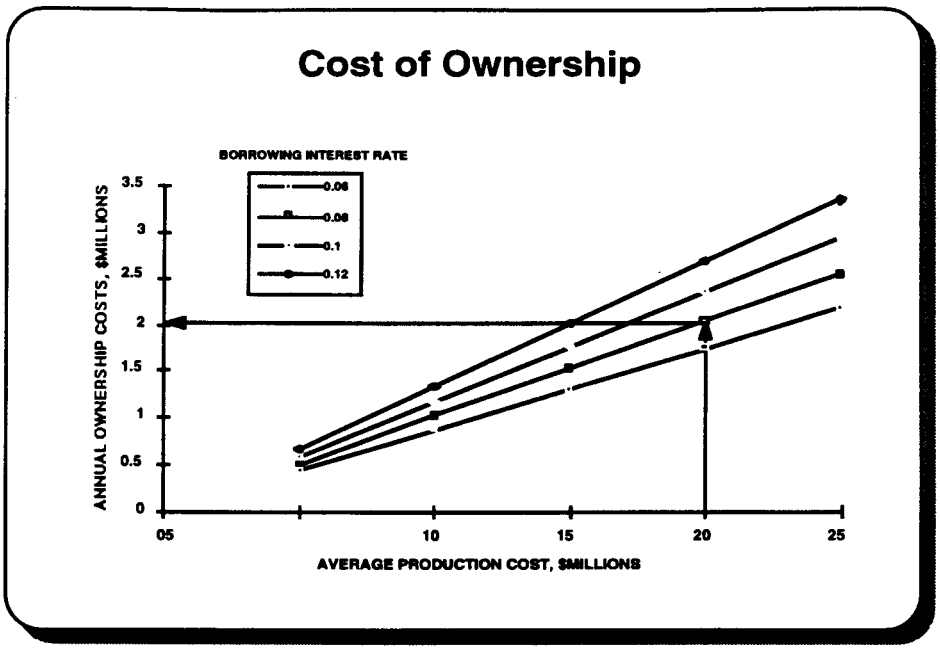
Although advanced technology can make rotorcraft substantially more cost-effective in both passenger and cargo configurations, these aircraft still fall far short of turboprops in competing on the basis of ticket prices. The industry must look to other factors—for example, reduced infrastructure costs, lower ground transportation costs and reduced travel time—if it is to capture a viable share of the market. Interestingly, the infrastructure value of the current commercial air transport system is much greater than the value of the fleet because of the enormous public/private investment in land and terminal facilities.

Impact of Lean Manufacturing on Rotorcraft Total Operating Cost

- **Lean manufacturing can reduce manufacturing cost and, to a lesser extent, spares cost. Estimates by Boeing on 777 are 25–35 percent reduction.**
- **For operating rates that commercial operators would have to fly to make a profit (1500–2500 hrs/yr), operating costs dominate ownership costs.**
- **The estimated overall reduction in cost is about 10 percent, rotorcraft/turboprop cost ratios are 1.8.**

We also looked at the application for "lean" manufacturing or improved product processing to further reduce rotorcraft production costs. Boeing has claimed that its 777 vehicle may be some 25–35 percent lower in cost using these newer manufacturing concepts, compared to the older methods. If lean manufacturing could be applied to rotorcraft examined in this study, and using 30 percent as a typical production-cost reduction, one could expect that the cost of ownership and even some insurance costs would drop proportionately. But as the next several charts will show, ownership costs are only about one-third of all costs; direct and indirect operations costs account for the balance.

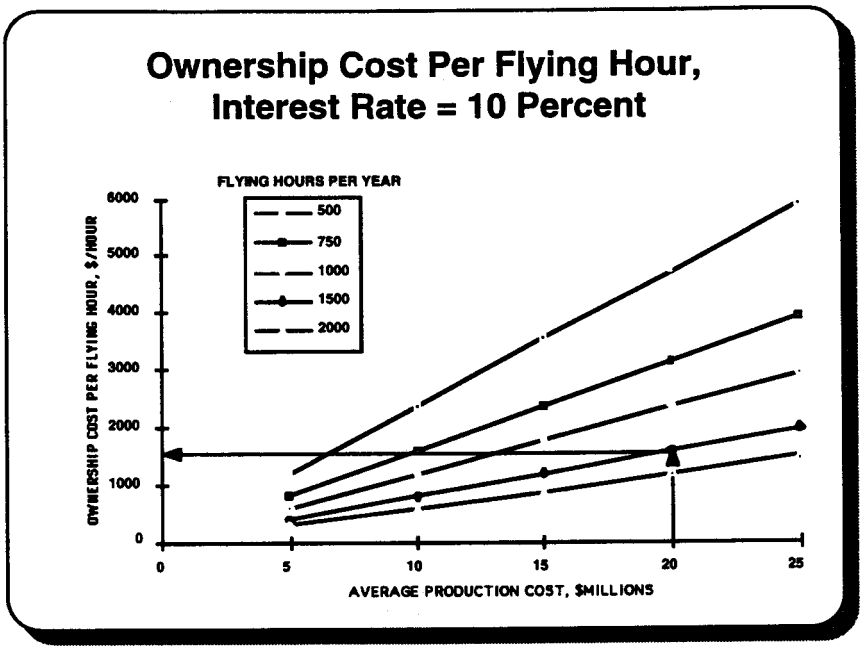
The operating tempo, i.e., the number of hours flown per day, would have to increase substantially over what scheduled passenger helicopters have flown in the past. However, 1,500–2,500 hours per year is what commuter airline airplanes are currently flying, compared to much lower numbers for existing rotorcraft.



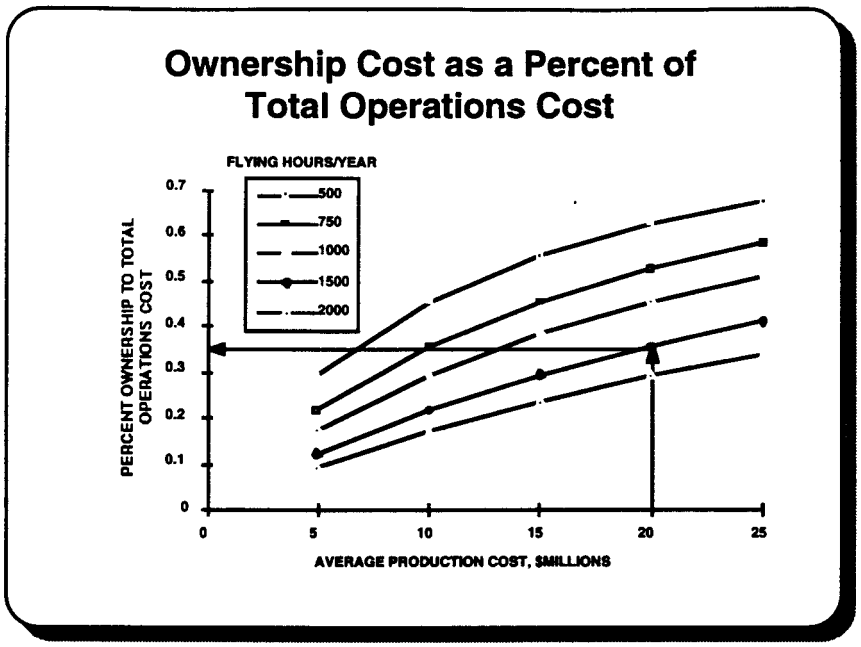
The next three charts examine the cost of ownership (acquisition costs excluding RDT&E). The first looks at the cost of acquiring a new rotorcraft whose average production cost varies between $5 million and $25 million. With the expected cost of a 40–44 passenger rotorcraft in the range of $20–25 million, the $20 million point was chosen. An annuity value was calculated for varying interest rates, a fixed 20-year lifetime, and zero regional value, and then it was divided into the estimates of average production cost to get the annual cost of ownership or leasing, in this example about $2 million. This is essentially the sum of interest expense and depreciation charges annually.

The Army does not break its costs down in this manner; it has separate procurement and operations budget categories. But commercial airline operators do include cost of ownership as an operations cost, so we are doing so in this analysis since the procurement decision will be made in the commercial sector, not the military sector.

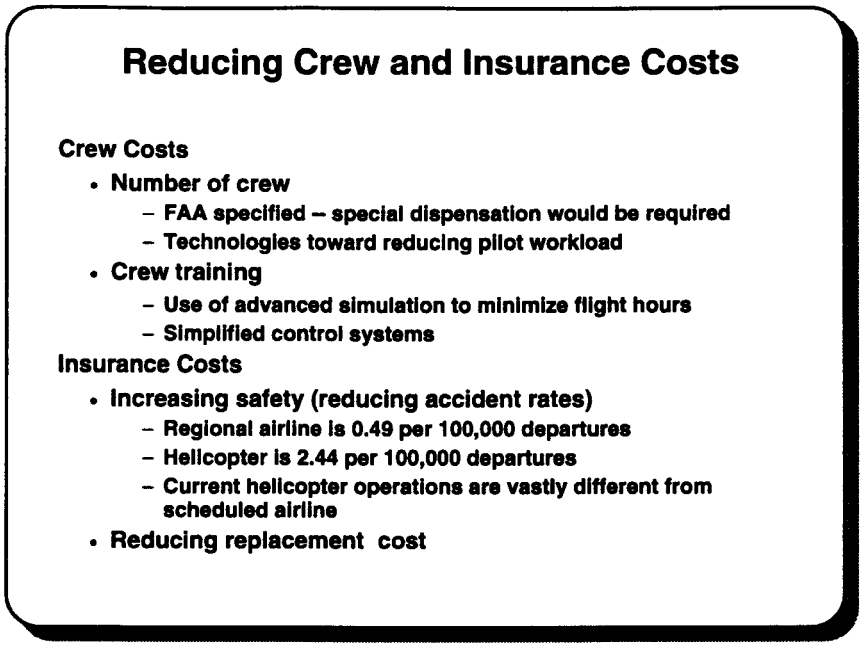
The cost per seat of the rotorcraft above is at least 40 percent more than the cost per seat for a 737. The 737 costs include the amortization of RDT&E expenses, so on a comparable basis the gap is even greater.



Taking the $20 million production cost from the previous chart, we next picked an interest rate of 10 percent, which should be the minimum current rate for borrowing for a relatively risky project such as a scheduled rotorcraft passenger service. At this rate we can calculate the ownership costs per flying hour for a range of annual flying hours. The Army currently flies its helicopters an average of 40 hours or less each month, or about 500 hours per year. As the chart illustrates, this is the smallest number of flying hours shown, because for a scheduled passenger service, many more hours must be flown in order to be profitable. We show rates for up to 2,000 hours per year, which is only 5.5 hours per day, lower than long-haul traffic but in the ballpark for commuter service. It is certainly possible that 2,500 or even 3,000 hours per year could be flown if the rotorcraft operation is profitable, but we weaken the argument for the benefits of "lean production" if we have a low percentage of ownership cost relative to the other operations costs; in fact, some of the other operations costs could increase with very high flying rates, i.e., crew, fuel, and maintenance. Obviously, utilization rates that are four times current practice are a major challenge to rotorcraft manufacturers. We believe that high flying rates are a *sine qua non* for profitability of operations, and should become a strict requirement.



Finally, if we add the ownership costs from the previous chart to the other operating costs from the CH-47D, admittedly a helicopter rather than a generic rotorcraft, and which may be somewhat higher than say, a tiltrotor, we can calculate the impact of ownership costs and look at the effect of lean production. If the rotorcraft costs in the range of $20–25 million—lower would weaken the argument—and we look at the 1,500 flying hours per year line—greater would weaken the argument—we see that ownership costs are about 33 percent of total operations costs. According to preliminary Boeing estimates on the 777 project, they believe they can lower production costs using lean manufacturing techniques by about 25 to 35 percent. Using 30 percent as an average, it is apparent that ownership costs as a percentage of commercial operations cost could be reduced by 33 percent times 30 percent, or 10 percent overall.



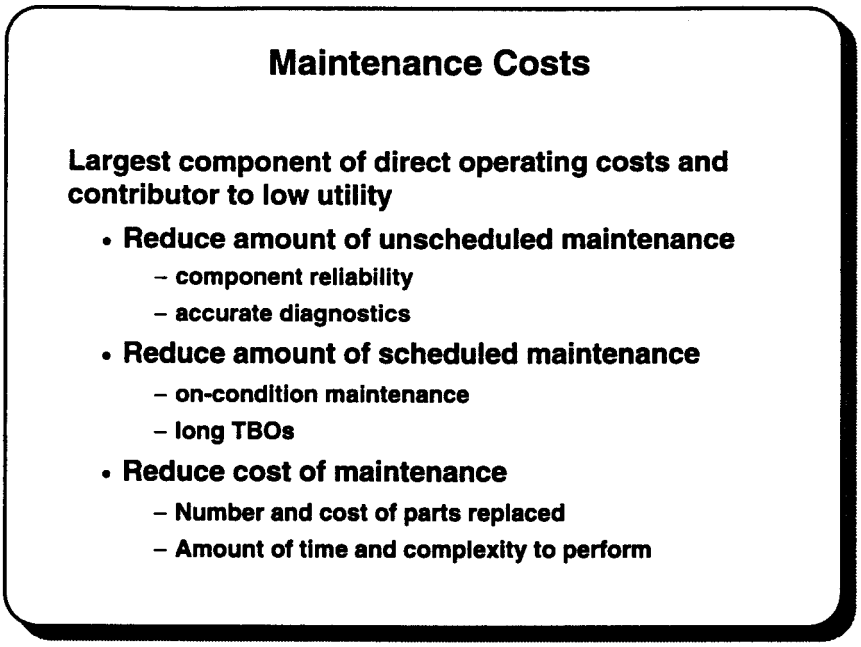
As previously shown in the breakdown of rotorcraft operating costs, crew time and insurance rates collectively make up approximately 35 percent of the total. Advanced technologies could potentially offer several ways to reduce these operating cost categories through improvements in measures of merit such as reduced pilot workload or lower accident rates.

The number of crew members required on board an air vehicle is specified by the FAA in a series of Federal Air Regulations (FAR). The FARs that apply to commuter airlines and emergency medical helicopters (part 135 and part 121), among other users, require that two crew members be in command of the vehicle. This is due to pilot workload issues, the need for accurate decisionmaking, and the potential for one pilot to be suddenly disabled. Since reducing the number of pilots from two to one could lead to large cost reductions, the first hurdle is to obtain an exemption from the FAA. This approach would most likely have to be taken in combination with workload-reducing technologies such as coupled autopilots and automatic engine controls. It is interesting to note that recent events have forced the FAA to rethink this regulatory structure and force part 135 commuter airlines to comply with the more stringent part 121 regulations. How these actions will affect helicopter operators remains to be seen at this time. A solution less dependent on regulatory change and thus more likely in the short term is simply to reduce the time and cost of rotorcraft training, while improving its effectiveness. The use of advanced digital control systems to make a rotorcraft as simple to fly as an airplane is technically possible, and could lower training costs and times. High-

fidelity flight simulators are used throughout the commercial fixed-wing and military rotary-wing fleets, but have seen little commercial rotorcraft application. In an industry where flight hours are extremely expensive, such systems could generate returns on investment to an operator relatively quickly.

Insurance rates, both hull and liability, are a strict function of safety, both perceived and real. Historically, helicopter accident rates have been around three to five times higher than those of turboprops, with hull insurance rates approximately the same factor higher. However, these rates are extremely variable and are based on an operator's record and type of operations. It should be noted that much of this difference is probably due to the riskier nature of helicopter operations (crop dusting, line inspections, etc.) as compared to the mission turboprops typically perform. Scheduled helicopter passenger operators have a quite good safety record, although passengers have proved to be extremely sensitive to isolated accidents. Liability insurance cost has typically been quite small for helicopters, due to the small passenger loads, but an airline-type operation would see liability rates rise to at least regional airline levels.

In order to inform insurers of the true risk of a combination of vehicle type and operation, safety could be demonstrated in an effort similar to that used by the FAA for Extended Twin Operations Over Water (ETOPS) certification. Some set of safety-related technologies such as better civilian crashworthiness, GPS ILS, one engine inoperative (OEI) certification through contingency-rated engines, and artificial vision might be required to achieve the required safety levels in such a demonstration. Rotorcraft have been considered inherently more dangerous than fixed-wing aircraft. However, in a scheduled airline operation with regular routes, air traffic control, and increased FAA oversight, safety should be much higher than achieved by helicopter operators today.



Maintenance costs are the single largest contributor to the direct operating costs of today's helicopters. Any new rotorcraft must control these costs in order to succeed. Downtime due to scheduled and unscheduled maintenance is expensive.

The task of reducing maintenance costs can be simply broken down into two categories: reducing the amount of maintenance and reducing the cost of maintenance. Both scheduled and unscheduled maintenance procedures are amenable to several technology-dependent measures. The key to reducing the amount of scheduled maintenance is to move toward performing maintenance only as needed, not on a schedule fixed by life-limited parts and time between overhauls (TBO). Long-lifetime parts tend to be extremely expensive, however, so moving toward simpler systems with fewer parts would be a likely adjunct technique. However, accurate diagnostic tools and monitoring systems are then required to ensure that safety is not compromised due to the longer periods between inspections and repairs. These onboard health and usage monitoring systems (HUMS) can offer varying levels of monitoring and detection, as well as imminent failure warning to pilots.

Unscheduled maintenance could also be reduced through HUMS via their potential ability to predict component failure. (Unscheduled maintenance is likely to be associated with low reliability and equipment failures that reduce availability for service.) Active vibration damping would also increase part lifetimes, but simply reducing the complexity and increasing

the durability of components and systems is the most obvious method. Component testing to several lifetimes worth of use could be used by manufacturers to predict failure points and bring early fixes into service. Some weight and performance losses will be seen from trends such as de-rated engines and overbuilt parts, but the current gap is in passenger acceptance and cost performance, not aerodynamic performance. With most current helicopter designs derived from military products, the military preference toward performance at the expense of cost has certainly affected civilian rotorcraft operators.

The costs of maintenance procedures are set by parts needed and the amount and complexity of the labor performed. Cheaper parts most likely will result from simplicity and new materials, although this goal is in conflict with that of increasing lifetimes. New composite materials and forming techniques may offer relief from this dilemma. Commercial vehicles designed with multiple easy-access paths and line-replaceable units can significantly reduce maintenance procedure times and could potentially reduce the amount of training required for mechanics. Maintenance trainers and simulators could serve the same purpose.

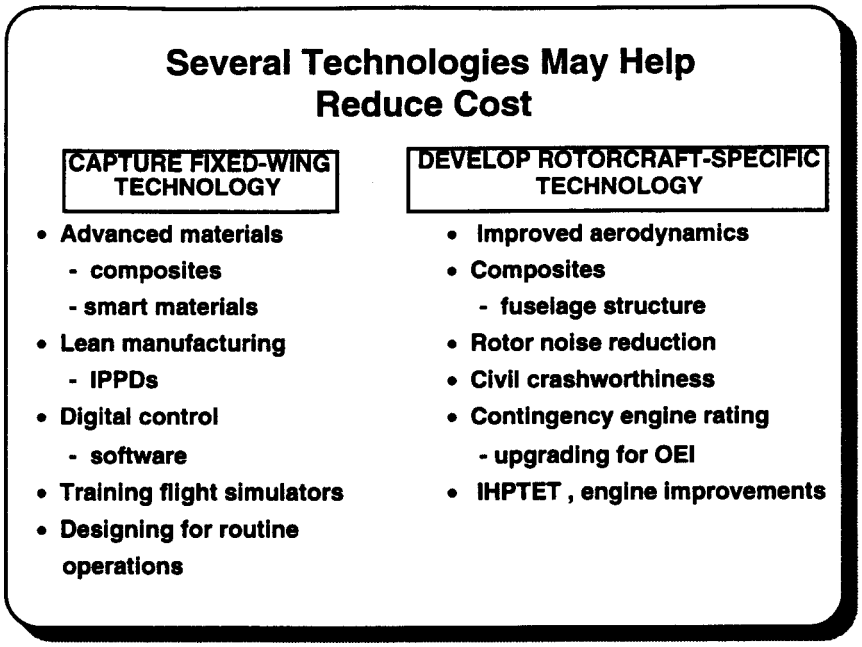
In order to estimate the magnitude of savings that may be seen through improvements in maintenance costs, the cost breakdowns for the CH-47 shown earlier are used. Depreciation and interest account for 30 percent of operations cost; insurance, crew, and maintenance labor are 10 percent each; parts costs are 25 percent; and fuel, overhead, and taxes total the remaining 15 percent. Thus, if parts costs and the amount of labor performed were reduced by 30 percent, the total effect would be to reduce operating costs by a further 10 percent.

Technologies and Measures of Merit

	SAFETY		DEPENDABILITY		MAINTENANCE				PERFORMANCE	
	reduced pilot workload	crash avoidance and survival	component reliability	accurate diagnostics	on-condition maintenance	parts count	shorter procedures	lighter weight	lower drag	higher utility
vibration damping			X					X		
artificial vision	X	X								X
bearingless rotors			X			X	X	X	X	
composite fuselage		X				X	X	X	X	
composite parts			X			X		X		
de-rated engines		X	X							
electrical actuation	X	X	X	X		X	X	X		
GPS ILS	X									X
HUMS			X	X	X					
onboard trail and balance							X			
simplified controls	X	X								
wire-strike warning		X								

One simple approach proposed to weigh the advantages and disadvantages of various technologies is the Quality Function Deployment (QFD) technique. With this method, the technologies (generally termed "hows") are arranged as the first column, and the measures of merit (called "whats") as the first row. Each intersection then has some value, either positive or negative. For instance, de-rating of engines is "how" you increase safety, but a penalty is paid in the "what" of reducing weight. The procedure of assigning weights and values is necessarily involved, and requires the expertise of those intimately familiar with both the technologies and their applications.

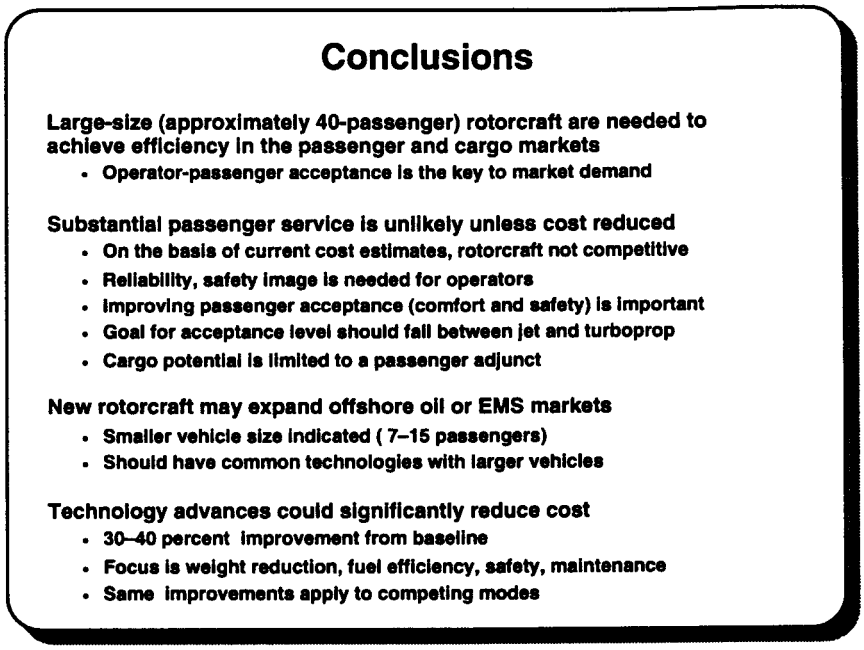
The chart shown is meant to be an example using the previous discussion as a base, not as an exhaustive list of "hows" or "whats." The categories discussed in the previous charts are shown across the top, along with the various measures of merit (whats) that apply to them. Note that some, such as more reliable components, apply to both increasing safety and reducing maintenance costs. A wide variety of potential technologies are also listed. Instead of attempting to assign weights and values on the chart, we used a simple marking scheme to show where certain technologies might apply. Detailed analysis is necessary to make such a step. In our example, however, technologies such as composites, electrical instead of hydraulic actuator systems, and bearingless rotor systems would all seem to be particularly high leverage.



Our study indicates that a combination of efforts will be required to control costs sufficiently to support large viable markets. Reducing the cost of rotorcraft through technological improvements may benefit from developments that help fixed-wing aircraft. In addition, several technologies that are rotorcraft specific should be pursued, especially in the areas of safety assurance and noise reduction. Methods that help design for routine operations help the flow of scheduled service and reduce uncertainties that lead to safety problems. Flight and maintenance simulations can be highly effective in improving performance and indirectly lowering operating cost.

In materials, there should be an emphasis on developing low-cost composite production that could benefit the fuselage in addition to the more limited applications now seen in civil aircraft. Smart materials might be found to help with active control mechanisms for rotor blades, which we have seen could increase the viability of a passenger market.

A number of other technologies are important. Engine performance should be developed, both for safety and efficiency. Methods that aid lean manufacturing contribute partially to the goal of reducing costs. Software development and maintenance is very important for the digital systems that have been created in avionics and control.



Scheduled passenger operations favor a large (40-passenger) rotorcraft, while niche markets favor a small (7 to 15-passenger) vehicle. Neither scheduled passenger service nor cargo, even as an adjunct to passenger service, will be economically feasible unless substantial cost reductions are achieved and passenger and operator acceptance is dramatically improved.

We believe there is at best only a remote possibility that, without government subsidies, commercial producers will invest in the RDT&E and production capacity necessary to build these rotorcraft.

A related but more controversial view is that the current commercial transport system involves a large investment in infrastructure, mainly land, terminals and groundsite access, compared to a much smaller investment in aircraft, and further increases in capacity are likely to entail extraordinarily large increases in infrastructure costs and complexity. Properly configured rotorcraft might have the ability to increase short-haul capacity within the existing infrastructure investment. But to achieve this potential it will require a public/private partnership that differs considerably from the current air transport system. This deserves further study to explore how such a partnership would reduce the costs of adding capacity.

Recommendations

The Army should focus on dual-use technologies that are applicable to small rotorcraft as well as to large ones (e.g., CH-47D)

- **A CH-47D replacement is not likely to arise from dual-use rotorcraft development**

The Army should pursue technologies that reduce rotorcraft costs while improving passenger and operator acceptance

- **Commercial versions require an emphasis on reliability, safety, noise and vibration reduction in excess of military needs**
- **"Lean production" may result in reduced production costs of up to 30 percent, but that amount is too little to make rotorcraft competitive**

Our market analysis shows that there are two new rotorcraft that could potentially be viable future designs. The first is a small (7 to 15 passenger) vehicle suitable for emergency medical service, the domestic offshore oil market, and other, more general, utility uses. The second is a large (30 to 40 passenger) vehicle suitable for scheduled passenger operations, joint passenger and cargo routes, and the foreign offshore oil market. The latter vehicle is also the size required for a CH-47D replacement. While neither of these configurations now appears to be economically feasible, we recommend that studies be directed at designs that will share the same technology, thus reducing both RDT&E and procurement costs.

We also investigated "lean manufacturing," or improved product processing, as a means of further reducing rotorcraft production costs. Boeing has stated that by using newer production methods, the cost of the 777 vehicle may be reduced by 25 to 35 percent. If lean manufacturing could likewise be applied to the rotorcraft examined in this study, and using 30 percent as a typical production cost reduction, one could expect that the cost of ownership, and even perhaps some insurance costs, would drop proportionately. However, ownership represents only a third of total rotorcraft costs. Direct and indirect operations account for the balance. With improvements in maintenance and parts costs, reductions on the order of another 10 percent could also be achieved.

Our findings suggest that rotorcraft do not compete well against fixed-wing service if the two types of service compete in the same market. But

the expanded role of regional airlines suggests that airline decisions, and not necessarily passenger preference, has dictated the rise of commuter service using turboprop aircraft. If the carriers and airport operators determined that rotorcraft are the proper mode for expanding short-haul capacity, then traveler preference would be far less important than if rotorcraft are in a head-to-head competition with fixed-wing equipment.

Therefore, our final recommendation is that a careful pilot analysis of the tradeoff between rotorcraft performance and infrastructure enhancement needed to accommodate increases in capacity should be performed. This analysis would attempt to quantify whether and how existing infrastructure could be leveraged by suitable rotorcraft design to reduce the need for large new investments in land and terminals.

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