loadings, and that developments in this direction are equally important.

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Comparative Projections of Low-Disk-Loading VTOL Aircraft for Civil Applications

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The technical and economic characteristics of three types of low-disk-loading VTOL aircraft for short-haul civil transport in 1985 are forecast. Comparisons of the types indicate that all three will find applications in the civil market of the future and that selection of one type in preference to another depends principally on requirements of aircraft size and operating stage length. In all size and payload categories, the helicopter will have the lowest cost per seat-mile for short stage lengths (10 to 25 naut miles). In larger transport categories (30 to 60 passengers), the compound helicopter will become cost-effective relative to the helicopter when it is designed for a cruise speed 50% greater than that of the helicopter. The composite VTOL, represented in this study by the tilting-proprotor aircraft, is the most economical in the larger transport categories at stage lengths greater than 30 naut miles. This kind of aircraft, designed for a 400-knot cruise speed, will provide 100- to 300-mile intercity service at a fare-cost comparable to that of advanced-technology jet "airbuses," while operating either from airports or from VTOL terminals.

Introduction

THE possibilities for applications of VTOL aircraft in the urban transportation systems of the future are immense. They may range from the multitude of specialized tasks of today's small helicopter, through passenger and utility transport within a megalopolis, to intercity transport between city centers in direct competition with airplanes, buses, trains and other future modes of transportation.

In exploring this spectrum, four general classes of aircraft have been considered: executive class with payload capability up to 1200 lb (6 places), utility class with payload up to 2500 lb (12 places), light transport with 6000 lb (28 passengers), and medium transport with payload capability up to 12,000 lb (58 passengers). Helicopters, compound helicopters, and tilting-proprotor aircraft were developed for each class and perturbations of design cruise speed and design cruise range were examined for each. The independent parameters of the aircraft configurations that were studied are given in Table 1.

Design characteristics of these aircraft—such as gross weight, weight empty, fuel required, and installed power—were derived from technical characteristics that include the effects of predicted advances in technology for the 1975–1985 time period. The technical characteristics which have a significant impact on the results of the study are the lift-drag ratio, hover power loading, weight-empty-to-gross-weight ratio, and specific fuel consumption.

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Table 1 Configuration matrix

Aircraft class	Payload & crew, lb	Design cruise speed, knots		
		Helicopter	Compound helicopter	Tilting proprotor
Executive	1,200	150	175	200
		175	200	250
Utility	2,500	160	180	220
		180	220	300
Light transport	6,000	175	250	350
		200		
Medium transport	12,000	175	250	300
		200	300	350
				400

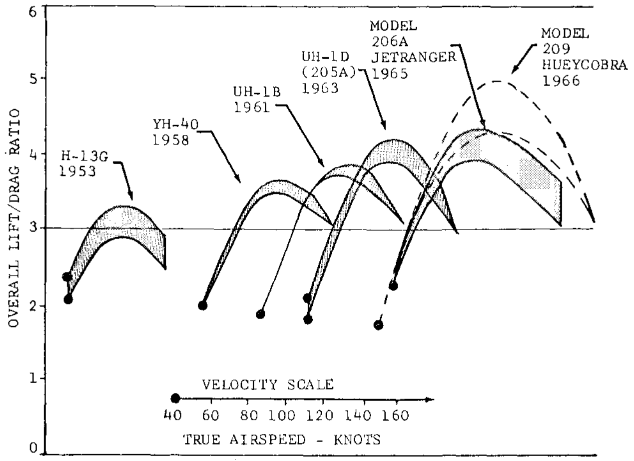

Fig. 2 Lift-drag ratios of current-technology helicopters.

Lift-Drag Ratio

Helicopter

A typical current-technology helicopter in the executive/light-utility class is shown in Fig. 1, hovering in a confined area over semiprepared/unprepared surfaces. This capability is, of course, the basic reason for the widespread and successful use of the helicopter today. In forward flight, the lift-drag ratios of this and other Bell helicopters are plotted in Fig. 2. Historically, these data show that, although maximum L/D and cruise speed have increased with time, L/D at cruise speed (about 90% of maximum speed) has remained nearly constant at a value of about 3.

These trends will continue in the future, according to our calculations. Advanced-technology helicopters will benefit somewhat from improved blade drag coefficients and to a greater extent from reduced airframe drag. Typical airframe drag values are shown in Fig. 3.[1-5] Results of L/D calculations including these improvements are given in Table 2 and show that over-all lift-drag ratios of about 3 to 4 will be maintained in the small helicopters at cruise speeds up to 150–180 knots and in the large helicopters up to 200 knots.

Compound Helicopter

The compound helicopter is one promising means for achieving speeds beyond those at which the lift-drag ratio and propulsive efficiency of the pure helicopter seriously decrease. One of several such experimental aircraft is shown in Fig. 4. For the compound helicopters the rotor was assumed to be unloaded in lift and slowed in cruise to 70% of the hover rpm.[6] Over-all lift-drag ratios (Table 2) are equal to or better than those of the helicopter, and they are attained at higher speeds.

Tilting Proprotor

In the tilting-proprotor approach to increasing the productivity of the helicopter, the rotors are tilted forward 90° to act as propellers in high-speed flight. Lift is provided by the rotors during helicopter flight and is transferred to a high-aspect-ratio wing in forward flight. The rotors are then tilted back, with their masts vertical, for landing.

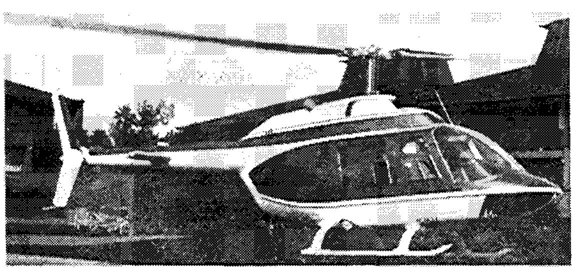

Fig. 1 Bell JetRanger hovering.

A 60-passenger commercial aircraft designed to NASA specifications for a 500-statute-mile-range VTOL transport is shown in Fig. 5. Its four T64 engines power two four-bladed counterrotating proprotors with a diameter of 46 ft. Disk loading is 15.5 psf in hovering flight, and maximum speed is about 400 knots in forward flight.

Calculated lift-drag ratios are shown in Table 2. The principal advantage of the small tilting-proprotor aircraft is its higher design cruise speed. For the larger aircraft, however, both lift-drag ratio and design cruise speed increase. For the medium transport designed for a cruise speed 50% greater than that of the helicopter, the ratio is over twice that of the helicopter.

Hover Power Loading

Installed power of each aircraft was determined by its cruise power loading (based on L/D) or hover power loading, whichever was greater. The predicted values of hover power loading shown in Fig. 6 reflect benefits from improvements in manufacturing techniques, tip shapes, and blade airfoils, thickness, and planform.

Weight-Empty-to-Gross-Weight Ratio

To determine the variation of empty weight with time, component technologies for airframe and rotor structures, power plants, and drive systems were projected to the 1978 period.

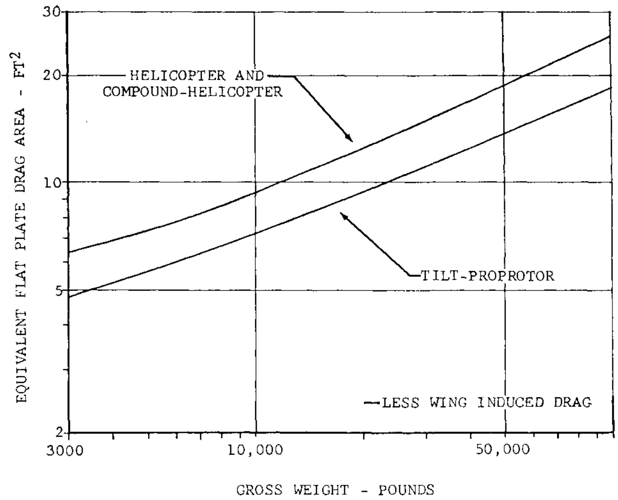

Fig. 3 Airframe drag of advanced-technology aircraft.

Table 2 Technical characteristics

Payload & crew lb	Helicopter				Compound helicopter				Tilting proprotor			
	Cruise speed, knots	Cruise alt., ft	Lift-drag ratio	Disk loading, lb/ft²	Cruise speed, knots	Cruise alt., ft	Lift-drag ratio	Disk loading, lb/ft²	Cruise speed, knots	Cruise alt., ft	Lift-drag ratio	Disk loading, lb/ft²
1,200	150	3,000	3.47	6.3	175	5,000	3.41	8.5	200	5,000	3.52	10
	175	3,000	2.79	6.5	200	5,000	2.76	8.5	250	5,000	2.75	10
2,500	160	3,000	3.81	6.0	180	7,500	5.09	8.0	220	7,500	5.15	12
	180	3,000	3.39	7.5	220	7,500	3.73	9.5	300	7,500	3.38	12
6,000	175	3,000	4.30	6.5	250	10,000	4.47	10	350	10,000	4.5	15
	200	3,000	3.46	8.5		20,000	5.4	10		20,000	6.0	15
12,000	175	3,000	4.88	8.5	250	10,000	5.65	8.5	300	10,000	8.11	15
	200	3,000	4.09	8.5		20,000	6.62			20,000	10.0	
					300	10,000	4.42	12.0	350	10,000	6.25	15
						20,000	5.83			20,000	8.3	
									400	10,000	4.98	15
										20,000	6.52	

The projections were applied to representative ratios of weight empty to gross weight for current-technology, fully equipped helicopters, compound helicopters, and tilting-proprotor aircraft (Fig. 7).[2,7]

Turbine Engine Characteristics

Power-to-weight ratio, specific fuel consumption, and design for VTOL operation will be enhanced by improvements in compressors, combustion chambers, and power-turbine technology. Specific fuel consumption of turboshaft gas-turbine power plants operating at maximum continuous power is projected to 1980 in Fig. 8. The band represents differences due to engine size.

Fig. 4 Experimental high-performance compound helicopter.

Design Characteristics of the Synthesized Aircraft

Gross weight, installed power, payload-to-gross-weight ratio, and payload-ton-knots per ton of empty weight, based on the projected technical characteristics, are given in Table 3 for the design speeds and payloads of Table 1 and for design cruise ranges of 200 and 400 naut miles.

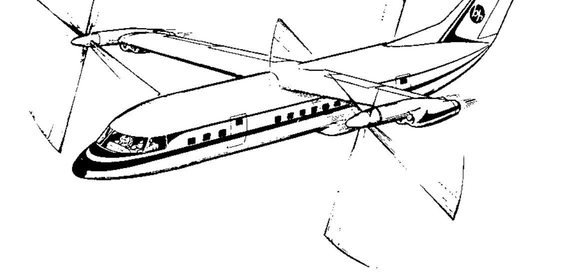

Fig. 5 60-passenger short-haul VTOL transport.

Life-Cycle Cost

The economic characteristics of each of the synthesized aircraft were derived from life-cycle costs. From these, costs per flying hour were calculated and, subsequently, fare costs, in terms of 1967 dollars. In life-cycle costs, tooling for aircraft manufacture is included, but not the development of the aircraft, engines, and avionics. Costs were categorized as fixed costs or operations and maintenance costs, and were calculated per aircraft and per flying hour.

Fixed Costs

Fixed costs include the costs of aircraft and spares purchase, hull insurance, and interest. The quantity of each class (Table 4) was selected for the aircraft with the minimum cruise speed, and the quantity for other aircraft types performing the same function was varied inversely with cruise speed. The aircraft purchase cost is the sum of the costs of manufactured weight, engines, avionics, and other installed equipment. A cost per pound of manufactured weight was determined for a representative aircraft of each type, and curves with 90% slope were used to account for variations in production quantity and manufactured weight. Engine costs for the appropriate horsepower and purchase quantity were derived from Watts's data.[8] Weight and cost allowances were derived for avionics and other equipment.

The purchase costs of aircraft and spares were depreciated on a straight-line basis over a 10-yr period, to a 15% residual value. Annual allowances were provided to cover the costs

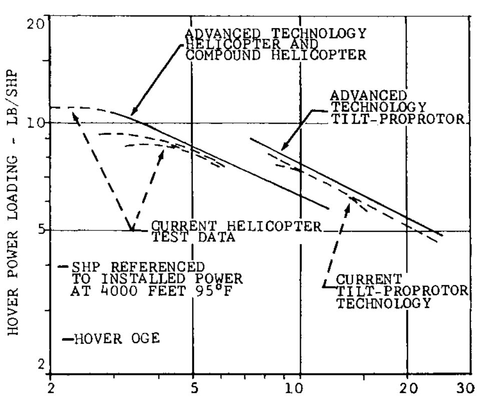

Fig. 6 Hover power loading.

Table 3 Design characteristics of the synthesized aircraft

	Helicopter							Compound helicopter							Tilting proprotor						
Payload & crew, lb	Cruise speed, knots	Design range, naut miles	Gross wt, lb	Install. power, shp	PL/GW	Productivity, ton-knot/ton	Cruise speed, knots	Design range, naut miles	Gross wt, lb	Install. power, shp	PL/GW	Productivity, ton-knot/ton	Cruise speed, knots	Design range, naut miles	Gross wt, lb	Install. power, shp	PL/GW	Productivity, ton-knot/ton
1,200	150	200	2,920	475	41	126	175	200	3,400	695	35	112	200	200	3,650	823	33	114
		400	3,830	623	31	96		400	4,820	985	25	79		400	5,200	1,172	23	80
	175	200	3,180	750	38	132	200	200	3,830	1,150	31	112	250	200	4,150	1,542	29	125
		400	4,630	1,090	26	91		400	6,050	1,800	20	71		400	7,500	2,790	16	69
2,500	160	200	5,650	973	44	149	180	200	6,200	1,192	40	136	220	200	6,400	1,155	39	156
		400	7,080	1,220	35	119		400	7,400	1,423	34	114		400	7,670	1,386	33	130
	180	200	5,800	1,160	43	163	220	200	6,670	1,667	37	153	300	200	7,200	2,700	35	185
		400	7,480	1,495	33	126		400	8,700	2,175	29	117		400	10,100	3,790	25	132
6,000	175	200	12,900	2,290	46	175	250	200	14,900	3,790	40	191	350	200	15,850	5,630	38	239
		400	15,320	2,720	39	147		400	16,720	4,740	36	170		400	17,450	6,250	34	218
	200	200	13,400	2,800	45	192												
		400	16,800	3,510	36	153												
12,000	175	200	24,600	4,920	49	186	250	200	27,950	5,350	43	207	300	200	27,900	6,830	43	241
		400	28,200	5,640	42	162		400	30,600	6,470	39	188		400	29,400	7,210	41	229
	200	200	25,550	5,100	47	205	300	200	29,250	9,050	41	234	350	200	28,700	7,300	42	274
		400	29,950	5,980	40	174		400	32,000	9,120	37	214		400	30,200	7,790	40	260
													400	200	30,300	11,100	40	291
														400	32,760	12.300	37	269

of hull insurance and interest on the investment. The annual fixed-cost contribution to total flying-hour cost was determined by assuming an activity level of 1000 flying hours per year per aircraft.

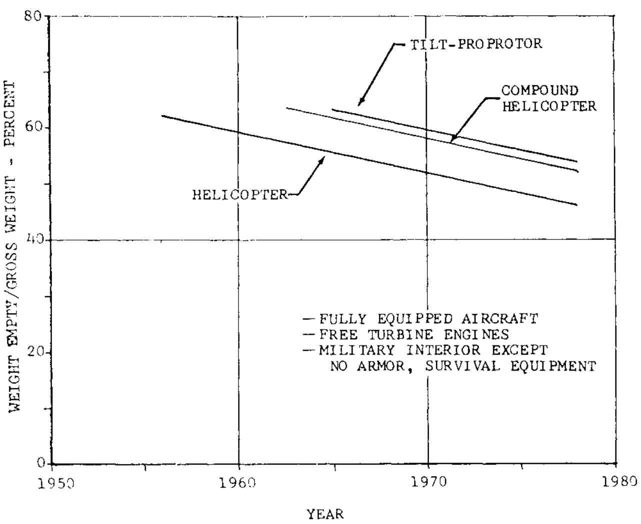

Fig. 7 Ratio of empty weight to gross weight.

Operations and Maintenance Costs

Operations and maintenance costs include the costs of crews, fuel, oil, maintenance and inspection labor, engine overhaul, airframe material, and overhead. Crew costs were assumed to vary as a function of aircraft class.

Fuel costs were determined from the fuel consumption for each aircraft. The cost per flight hour of maintenance and inspection labor was calculated on experience factors from commercial users of VTOL aircraft. It is 0.0000246 times the cost of aircraft purchase less engines.

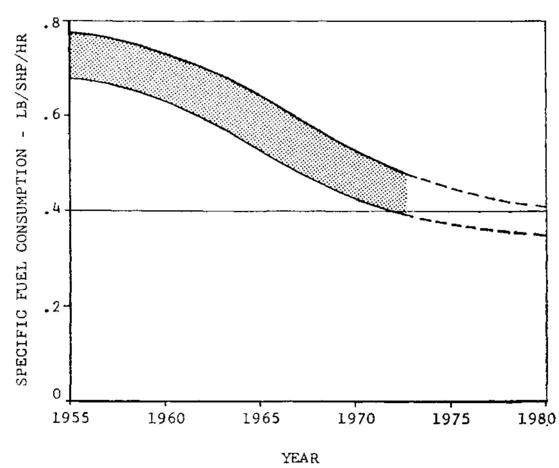

Fig. 8 Specific fuel consumption.

Engine inspection and overhaul costs per flight hour were determined as a function of engine horsepower, based on 1000 flight-hours' engine time between overhauls. Airframe material costs include inspection replacement items, overhaul components, and life-limited components. They were estimated as a single factor (0.00008) applied to the cost of aircraft purchase less engines.

Table 4 Aircraft production-run quantities

	Helicopter		Compound helicopter		Tilting proprotor	
Class/function	Speed, knots	Production quantity	Speed, knots	Production quantity	Speed, knots	Production quantity
Executive	150	1000	175	850	200	750
	175	850	200	750	250	600
Utility	160	1000	180	900	300	525
	180	900	222	725		
Light transport	175	500	250	350	350	250
	200	425				
Medium transport	175	500	300	300	300	300
	200	425			350	250
					400	225

Table 5 Life-cycle costs per flying hour

	Executive class			Medium transport class		
	Helicopter	Compound helicopter	Tilting proprotor	Helicopter	Compound helicopter	Tilting proprotor
Design range, naut miles	200	200	200	200	300	400
Design speed, knots	175	200	250	200	300	400
Design cruise alt, ft	3,000	3,000	3,000	3,000	10,000	20,000
Empty wt, lb	1,590	2,140	2400	11,750	16,810	17,850
Avionics wt, lb	117	117	117	292	292	292
Engine wt, lb	290	424	505	790	1,280	1,450
Manufactured wt, lb	1,183	1,599	1,778	10,668	15,238	16,107
Cost/pound of manuf. wt, $	59.70	77.10	79.0	47.4	61.0	67.7
Annual flying hours, hr	1,000	1,000	1,000	1,000	1,000	1,000
Cost of aircraft and spares						
Manufactured wt, $1000	70.6	123.3	140.5	505.7	929.5	1,090.5
Avionics & other equipment, $1000	20.0	20.0	20.0	50.0	50.0	50.0
Engines, $1000	66.0	81.4	86.0	169.4	220.0	258.0
Total, aircraft, $1000	156.6	224.7	246.5	725.1	1,199.5	1,398.5
Spares, $1000	31.3	44.9	49.3	145.0	239.9	279.7
Annual Fixed Costs/*FH*, $	32.58	46.70	61.52	150.80	249.50	290.90
Operation & maint. cost per *FH*						
Crew cost, $	15.50	15.50	15.50	40.00	40.00	40.00
Fuel & oil cost, $	6.30	9.07	12.70	34.08	61.01	58.20
Parts & labor, $	22.28	34.98	43.55	107.20	161.20	179.70
Overhead, $	11.47	17.62	22.50	56.60	88.88	95.16
Total opns & maint. cost/*FH*, $	55.55	77.17	94.25	237.88	351.09	373.06
Total cost per *FH*, $	88.13	123.87	155.77	388.68	600.59	663.65

All operations costs except crew costs were summed, and a factor of 40% was applied to provide overhead costs per flight hour. Total operations and maintenance cost per flying hour was then determined by summing crew, overhead, and all other operations and maintenance costs. Annual fixed costs prorated to 1000 flying hours per year were summed with total operations and maintenance cost per flying hour for all the 96 point-design aircraft considered. Several examples are shown in Table 5.

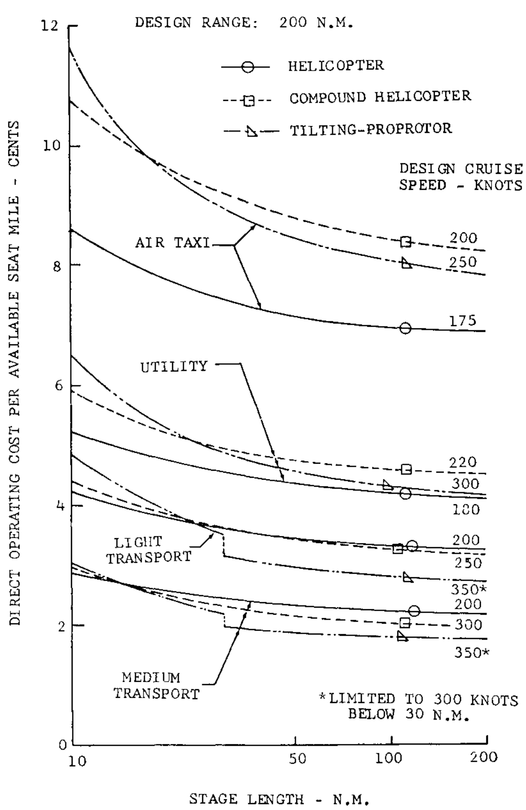

Fig. 9 Intracity direct operating cost.

Costs per Passenger-Mile

The principal criterion for comparison of alternative point designs was total fare-cost per passenger-mile. The determination of total fare-cost per passenger-mile was based on reasonable assumptions as to flight profiles, maneuver times, speed limits, and load factors. The assumptions were uniformly applied, and it was assumed that the total fare-cost per passenger-mile will include the operator's total cost per available-seat-mile divided by the load factor, 5% excise tax on the total income derived from the fare, 52% income tax on gross profits, and a net profit of 8% of the total income derived from the fare. For a 50% load factor, cost per available-seat-mile is multiplied by 2.5 to derive fare-cost per passenger-mile.

Cost Comparisons of Configurations

Comparisons of fare-cost per passenger-mile were made for two conditions: using each aircraft at its design range, and using each aircraft at intermediate ranges equal to or less than their design ranges (off-design-point operation). For the first condition, the comparisons show that within the limits of the design ranges studied (except for the air taxi and to a lesser extent the utility aircraft), the total fare-cost per passenger-mile of the advanced-technology aircraft is relatively insensitive to design range, even though gross weights vary by as much as 17%. There are no significant crossovers between configurations.

Costs for Intracity Operations

For the second condition, which is typical of intracity operation, Figs. 9 and 10 show direct operating costs and total fare-cost per passenger-mile as functions of stage length. In each of the four classes, an aircraft of each type, with a design range of 200 naut miles, was considered to operate over stage lengths from 10 to 200 naut miles.

As might be expected, cost is reduced as the size of the aircraft increases. Not necessarily to be expected, however, is the progressive reversal of the competitive position of each of the three types of aircraft as size increases, except at short stage lengths. At stage lengths less than 30 miles, the helicopter offers the lowest fare-cost and direct operating cost in all size categories. This advantage is retained in the larger size categories partly because of an air traffic control zone speed limit in congested areas. At stage lengths above 30 miles for the smaller aircraft, the helicopter offers the lowest costs and the tilting proprotor the highest. This relation reverses until for the larger vehicles, the proprotor aircraft has the lowest cost and the helicopter the highest.

Costs vs Payload

Figure 11 is a crossplot of fare-cost vs payload for the three types of aircraft at a design range of 200 miles. It shows the reversal in cost between the helicopter and the faster aircraft. If the curve is extrapolated to the right, it indicates fare-cost approaching that of the 200-passenger jet airbus designed specifically for short-haul operations from specialized ground facilities.

Intercity Costs

In Fig. 12, fare-cost is shown as a function of stage length for an aircraft of each type, operating at intercity ranges of 100 to 400 miles. These aircraft have design ranges of 400 naut miles and design cruise altitudes of 3000 ft (helicopter) and 20,000 ft (compound helicopter and tilting-proprotor aircraft). Not only is there a significant variation in costs (30%) among the three types, but also a large (100%) difference in cruise speed. In comparison with the helicopter that cruises at 200 knots, the tilting-proprotor aircraft, which cruises at 400 knots, significantly reduces passenger block time, and costs less. For a 200-statute-mile trip by a 60-passenger, 400-knot proprotor aircraft, direct operating cost is 1.4 cents per available (statute) seat-mile. This aircraft will provide 100- to 300-mile intercity service at a fare-cost comparable to current airline fares.

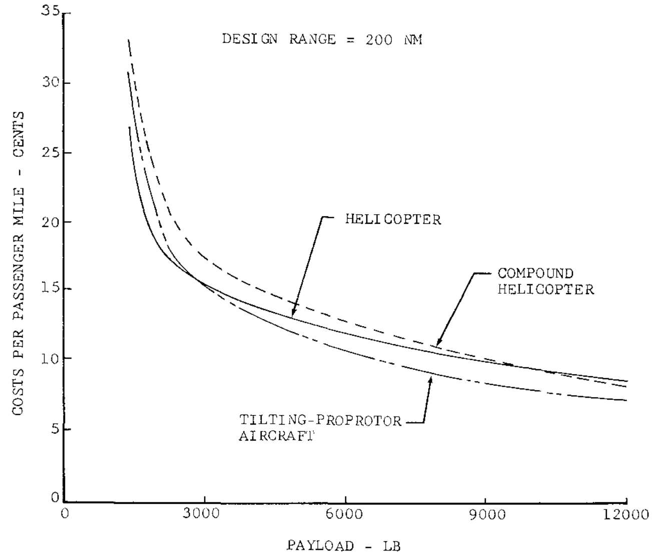

Fig. 11 Fare-costs vs payload.

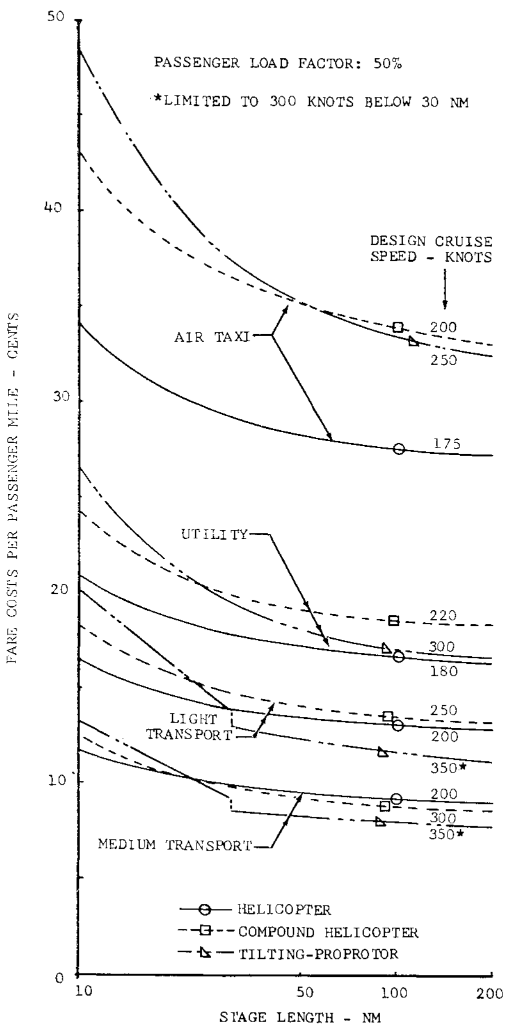

Fig. 10 Intercity fare-costs.

Conclusions

Selection of the specific type of low-disk-loading VTOL aircraft for the civil transportation network of 1985 will depend on requirements of aircraft size and operating stage length. All three types of aircraft—helicopters, compound helicopters and tilting-proprotor aircraft—will have the benefits of low disk loading, which include economy of installed power and the use of conveniently located helistops. The aircraft will have high vertical-lift efficiency and may encompass a wide range of cruise speeds.

Over all lift-to-drag ratios of 3 to 4 can be maintained in small helicopters at cruise speeds up to 150–180 knots and in larger helicopters up to 200 knots. Compound helicopters will have lift-to-drag ratios equal to or greater than those of the helicopter, and attainable at high speeds. For a tilting-proprotor medium transport aircraft cruising at 400 knots and 20,000 ft, the lift-drag ratio will be 1.6 times that of a 200-knot helicopter; and, at 300 knots, 2.4 times that of the helicopter.

The empty-to-gross-weight ratio of all three types of aircraft will be reduced by about 8% in comparison with current-

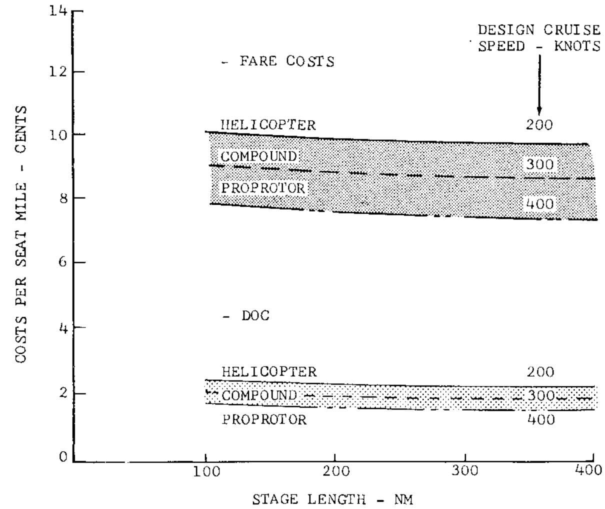

Fig. 12 Intercity fare-costs and direct operating costs.

technology aircraft. The tilting-proprotor aircraft will have the highest ratio. The helicopter will have the highest ratio of payload to gross weight in all payload classes at design ranges up to 200 miles. It will continue to be the preferred aircraft for the air taxi and utility functions. It may also be preferred for the light and medium transport functions when they are confined to intracity "multistop" operations; however, with the growth of requirements for long-stage-length intercity operations, higher-speed VTOL aircraft will usually be preferred.

Except in the medium transport class at long stage lengths, the compound helicopter will have a higher fare-cost than the helicopter. To gain a fare-cost advantage over the 200-knot helicopter at longer stage lengths, the compound helicopter should have a 50% increase in cruise speed. The tilting-proprotor aircraft will have significantly lower fare-cost per passenger-mile than the other aircraft types for light and medium transports in intercity operation, including possible intracity multistops.

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