

SECOND EUROPEAN ROTORCRAFT AND POWERED-LIFT AIRCRAFT FORUM

Introductory Lecture

ENERGY ASPECTS OF VTOL AIRCRAFT IN COMPARISON WITH
OTHER GROUND AND AIR VEHICLES

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ABSTRACT

It is emphasized that although the total energy consumption of helicopters (presently, the chief representatives of the VTOL field) is small in comparison with that of other modes of transportation, energy aspects have been, and will be extremely important for the development and expansion of rotary-wing aircraft applications. Energy expenditure per passenger-mile of presently operational helicopters is compared with that of other vehicles—first, on a statistical basis and then, through a more detailed study of a very-short-haul (intraurban) and short-haul (interurban—up to 200 n.mi.) operations. Possible ways of improving the energy standing of helicopters are considered in the presence of economic and environmental constraints. Presentation of a cursory procedure for minimization of overall penalties associated with the achievement of desired energy consumption gain concludes this presentation.

ENERGY ASPECTS OF VTOL AIRCRAFT IN COMPARISON WITH OTHER AIR AND GROUND VEHICLES

by

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1. Introduction

VTOL aircraft, presently represented almost exclusively by helicopters, being a part of the larger field of transport vehicles are subject to various forces and pressures acting on that field as a whole. In this respect, it is interesting to note that the attitude of the general public, government agencies, and even reputable technical organizations toward energy problems in general, but especially to those of transport vehicles, seems to run in cycles which tend to swing from one extreme of strong emotional involvement and bold plans for action to the other extreme of almost complete apathy and inactivity. Furthermore, those cycles seem to respond—usually with some time lag—to the unique "forcing function" of current fuel availability.

However, these changing moods and attitudes should not distract an impartial observer's mind from the fact that in the long run, there exists a very high probability that global supplies of petroleum will be considerably reduced in the relatively near future, probably within a few decades.

Concentrated efforts in many directions—ranging from sociopolitical and economic to purely technical—will be required to assure an orderly transition from the recent era of petroleum-based transportation systems to new forms. In the technical field, the two most important goals appear to be: (1) accomplishment of the same basic transportation missions by the petroleum-products powered vehicles, but at a lower expenditure of energy, and (2) studies and eventual development of new propulsion system concepts which will be in harmony with the trend toward new sources of energy.

At this point, one may argue that an improvement in energy economy may be the "to be" or "not to be" question for mass transportation systems such as the automotive complex or even commercial air transport; however, this problem should not be significant for civilian or military helicopters whose energy requirements amount to a drop in the bucket when compared with those of other modes of transportation. The fuel consumption of helicopters (both civilian and military) in the USA projected for the 1980s¹ would amount to about 0.15 percent of the total consumed by automobiles in 1970². In spite of this, perhaps fortunately for the sake of technical progress, energy aspects of helicopters cannot be ignored. A pointed reminder of that fact can be found from the events of three years ago when helicopter operators had to struggle for fuel allocations. For instance, New York Airways had to prove that in serving the public transportation needs, they were energy-wise, more efficient than such other means of transport as taxis and full-size private automobiles. Furthermore, the sudden increase in the price of fuel (Figure 1) strongly jeopardized the trend toward profitable operations of some helicopter transport organizations.

To those engaged in VTOL activities, the economic pressure to achieve better fuel utilization may be as strong as elsewhere, regardless of how small the total amount of fuel presently consumed by helicopters in comparison with that of other modes of transportation. *A headache is equally painful for a mouse as it is for an elephant.*

*Consultant

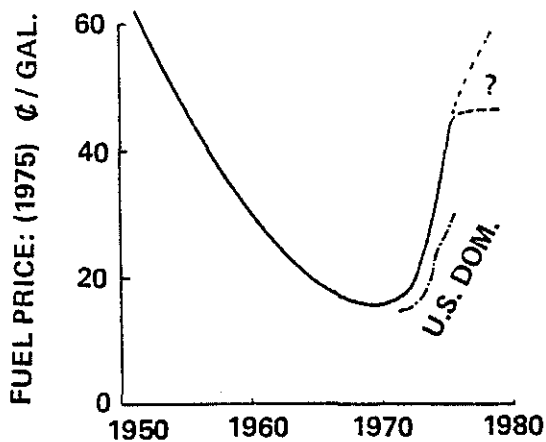


Figure 1. Price of fuel (in terms of U.S. cents) paid by the international airlines since 1950³

To assist the reader to form his or her own opinion about the energy problems of VTOL and potential remedies, the following aspects were taken into consideration: (1) an overview of the VTOL field and the accompanying energy problems examined against the background of other transportation systems, (2) more detailed study of energy aspects of helicopters, and (3) ways of improving energy consumption of helicopters.

2. An Overview of VTOL Energy Aspects

As in the past, the whole field of VTOL aircraft is represented almost exclusively by helicopters. However, the growing number of Harriers being used by the military, and a few of the experimental machines, may be cited as exceptions to this rule.

Also, in the future, the mix of VTOL aircraft may shift still further toward nonhelicopter configurations. The tilt-rotor may become an important representative of the coming rotary-wing generation, as exemplified by the flight research aircraft built by Bell which will be flown in the near future. Nevertheless, at the present time and through the Eighties, helicopters will probably dominate the family of VTOLs.

Excluding the USSR and China, it is expected that in the coming decade, U.S. civilian and military helicopters will each represent about one-quarter of the global helicopter population. The remaining two-quarters would again be almost equally split between international civilian and military groups (Figure 2)⁴.

Present helicopter sales are about evenly divided between North America and the rest of the world. However, because of the increasing demand of helicopters for development of new

Furthermore, there seems to be a dictum deeply rooted in the engineer's philosophy which, independent of temporary economic pressure and the political climate, seems to drive him toward finding ways of accomplishing a given task with the smallest expenditure of energy. This appears to be especially visible when dealing with moving objects ranging from high-velocity rockets and gun projectiles to slow-moving oil tankers.

In spite of the overwhelming importance of energy consumption and attempts to minimize the quantity used, one should not forget that many constraints may be encountered on the road to this goal. Some of them may be of an economic nature which can be related to the simple truth that after achieving some gains, further progress is just unaffordable. There may also be other constraints involving safety of operation, flying qualities, and finally, those related to environmental requirements such as noise and exhaust pollution.

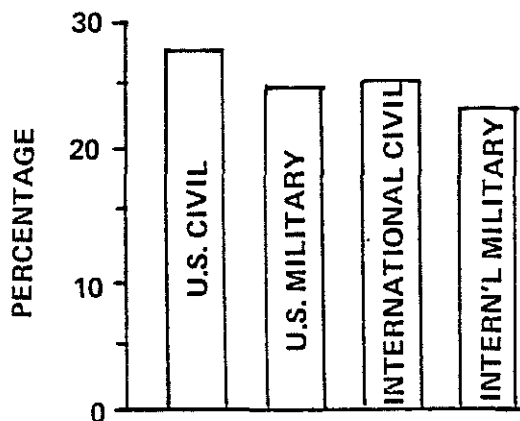


Figure 2. World helicopter distribution in the next decade

energy sources and agricultural demands*, this ratio may shift to 40 percent for North America and 60 percent for the rest of the world.

In spite of possible shifts in the relative distribution of helicopters between the U.S. and other countries, and between the civilian and the military, the U.S. civilian helicopters may be considered as a sufficiently large group to typically represent the growth trends and problems of the whole global helicopter population.

It can be seen from Figure 3 that deliveries of civilian helicopters on the North American continent now exceeds 500/year, and estimates for the total fleet by the end of the next decade range from approximately 23,000 to 28,000⁴. As to the distribution of that fleet, it can be seen from Figure 4 that general utility (industry, cranes, forest, agriculture, etc.) along with support of oil rigs represent the highest percentages. Non-military government agencies (both federal and local) are expected to maintain the highest relative growth rate^{1,4} (for instance, in 1974/75 the number of helicopters operated by those agencies rose 32 percent). A high rate of growth is also expected for the executive category.

As far as energy aspects are concerned, it should be noted that U.S. civilian helicopters are expected to log 2.5 million hours per year in 1980 and perhaps, as many as 6 million in 1985¹. The 1980 flight hours would consume about 350,000 metric tons of fuel per year. Although this figure may seem impressive to an average helicopter engineer, it should be realized that this represents only one-half of one percent of the yearly fuel requirements of 70 million metric tons projected for world airlines in 1980³ (excluding the USSR and China). In comparison with approximately 220 million metric tons of fuel actually consumed in the USA in 1970², the 1980 helicopter fuel consumption would represent a very modest 0.16 percent.

Some may tend to combine the above comparisons with the fact that in oil-rig support, ambulance service, police patrol, forestry, and agriculture, helicopters are used because they can do the job much better than any other available means. Beginning with this assumption, they may conclude that in the fields where helicopter flight characteristics make them operationally superior to other modes of transportation, energy consumption may become of secondary importance. The basic fallacy of this supposition was indicated in the Introduction. Here, we want to emphasize that even in those applications which are especially suited for helicopter operations, energy problems cannot be ignored, although they may appear in a different form; for instance, in the case of oil rig support in the U.S., oil rigs are presently located up to 150 miles from the shore (Figure 5).

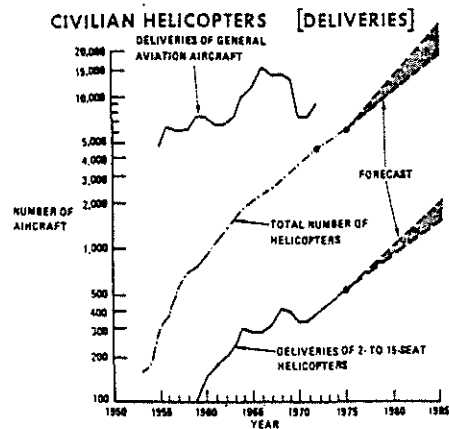


Figure 3. Deliveries of helicopters and general-aviation aircraft (N. American Continent)

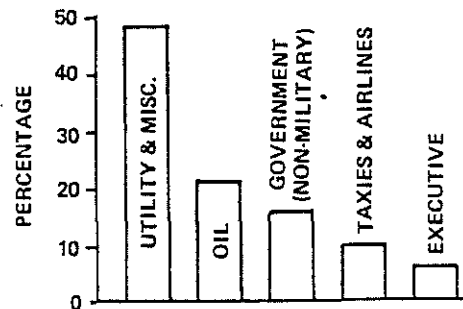


Figure 4. Civilian helicopter distribution in next decade

*Conventional application of seeds and chemicals requires 10 to 20 times more fuel than performing those tasks by helicopters¹.

With the expansion of existing oil fields and with the establishment of new ones (especially in the North where the Continental Shelf extends for several hundred miles from the actual shore), an improvement of the range/payload relationship becomes a problem. Here, obviously, the question of energy economy assumes the form of minimization of fuel consumption in order to cover these greater distances with the present, or even increased, payloads. It can be seen from Figure 6 that for short distances, at present the helicopter is superior to other concepts such as the tilt-rotor (which may appear on the horizon in the late 70s), or the tilt-wing (which has already been tested). When it comes to longer distances, however, then contemporary helicopters become inferior from the point of view of the payload/range relationship to these, and possibly other, concepts of VTOL aircraft.

Helicopters in Comparison with other Vehicles. The spontaneous growth of the helicopter field has been chiefly due to missions involving extended operations in hovering and near-hovering regimes of flight. This is probably not just coincidence, but is actually the result of a cause and effect relationship in that of all powered lift-generator concepts, the helicopter under static conditions shows the lowest energy requirements per unit of generated thrust.

In order to provide a comprehensive comparative scale for this energy consumption, specific impulse (I_s) is used:

$$I_s = T / \dot{W}_F \quad (1)$$

where T is the thrust (in pounds), and \dot{W}_F is the rate of fuel consumption (say in lbs/sec). Specific impulse, hence, can be interpreted as the hypothetical time (in seconds) that a given thrust generator could operate if the weight of the fuel were equal to the generated thrust. For VTOL configurations, this thrust can be assumed as equal to the gross weight for which \dot{W}_F is determined.

Eq (1) can be rewritten in terms of thrust specific fuel consumption ($tsfc$)_s as

$$I_s = 1 / (tsfc)_s \quad (1a)$$

In Figure 7, specific impulse for air-dependent generators is shown for the static condition, while for rockets, its value is, of course, independent of the state of motion of the vehicle.

This figure shows that rotary-wing aircraft having a specific impulse of over 70,000 seconds—compared to a few hundred seconds for chemical rockets—represent the concepts most suitable for operations where long times in hover and near-hover conditions are required.

In order to provide a yardstick for a quantitative comparison of various modes of transportation regarding energy consumption in horizontal translation, a concept similar to that of the specific impulse is proposed. It will be called the *specific distance* (D_s) representing a hypothetical distance (in n.mi) that a vehicle could travel if the weight of fuel is equal to the gross weight (W) for which the so-called specific range was established ($R_s \equiv$ distance traveled on one pound of fuel; n.mi/lb).

$$D_s = R_s W \quad (2)$$

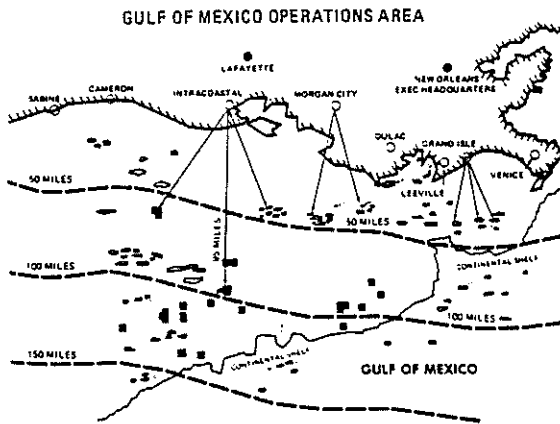


Figure 5. Typical support of offshore oil operations

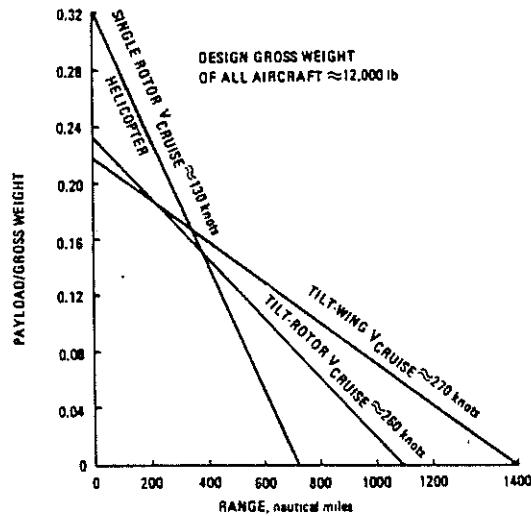


Figure 6. Comparison of payload/gross-weight ratios vs range

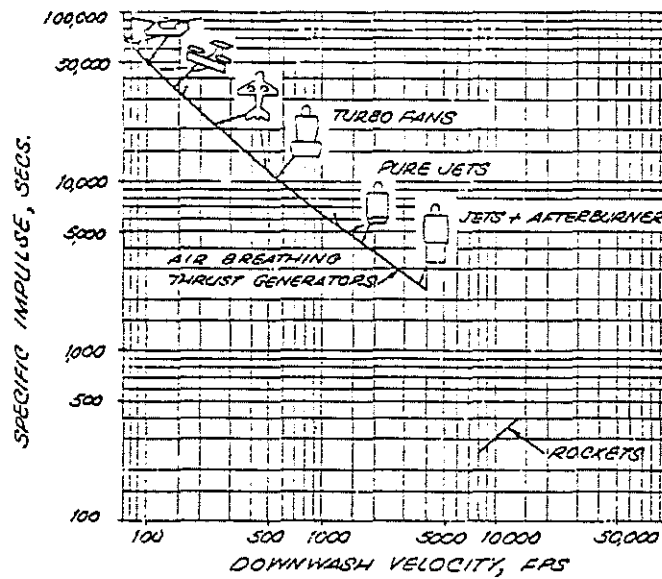


Figure 7. Specific impulse of various thrust generators

It is obvious that the specific range and hence, the specific distance, depends on the speed of motion. For bouyant water vessels as well as airships and wheel-supported ground vehicles, the R_s and D_s increase as motion speed decreases; while for aircraft (both rotary and fixed-wing), R_s and D_s maximize at the best range combination of flight altitude and speed.

Specific distances as a function of speed for helicopters, tilt-rotors (in the airplane mode of flight), automotive vehicles, and a dirigible are shown in Figure 8, and for other fixed-wing aircraft, D_s values are indicated at their optimum cruise speed-flight altitude combinations.

It can also be seen from this figure that in contrast to hovering, the helicopter in cruise shows much higher energy consumption levels per unit of gross weight and unit of distance traveled than other means of transportation. Tilt-rotors in the airplane mode of flight appear much better in this respect.

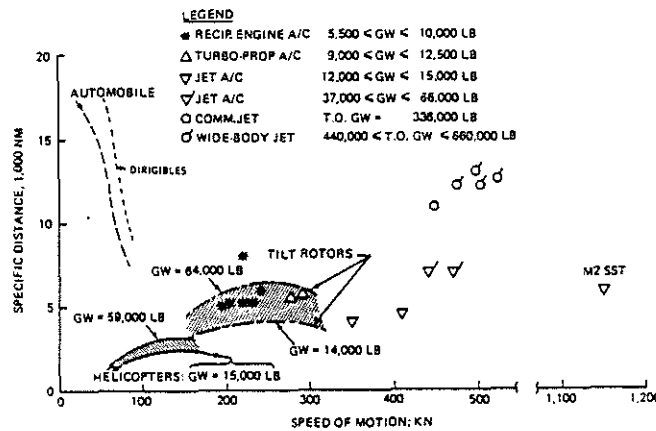


Figure 8. Specific distance of various vehicles

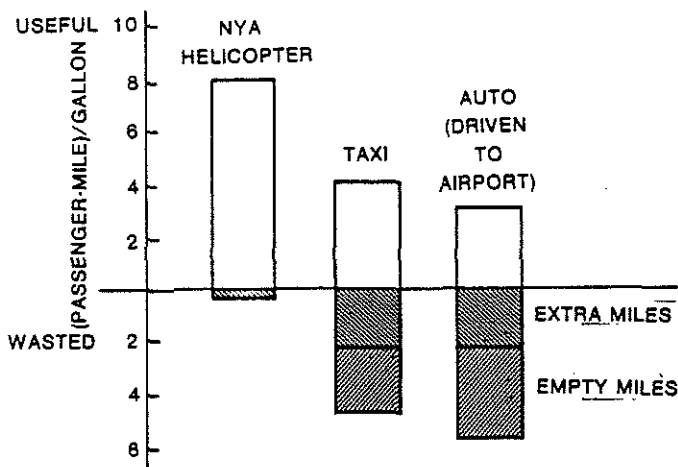


Figure 9. New York studies of fuel consumption⁵

However, this does not preclude the possibility that under certain circumstances—more direct routes or less wasted time in terminal operations—even the presently operational helicopters (1960 technology) may become competitive with other aircraft and ground vehicles as far as actual energy expenditure per passenger mile is concerned. Figure 9, based on New York Airway studies⁵, is shown as an example of the competition of helicopters with full-size automobiles and taxis in urban traffic.

3. Energy Consumption per Passenger-Mile

Actual expenditure of energy (say in BTU's) per passenger-mile was selected for this discussion as a common yardstick for assessing and comparing the energy efficiency of helicopters with that of other transport vehicles. This was done because it permits one to consider more factors (including sociological ones) than, say, a study of the energy aspects of purely cargo operations.

Total Energy Consumption. In order to make a meaningful comparison of energy aspects between various modes of transportation, it is necessary to know the total energy consumption per passenger and unit distance traveled (say, one n.mi.); TE/PNM . In that respect, the three most important factors are:

- (1) direct energy consumption per available seat-mile, $DE/S_{av}NM$;
- (2) all indirect energy expenditures associated with the operation (e.g., development of the right-of-way and manufacture of the vehicle itself)—also referred to seat-available and nautical mile, $IE/S_{av}NM$; and
- (3) load factor (LF) under which the vehicle actually operates:

$$TE/PNM = (DE + IE)/S_{av}LF. \quad (3)$$

Direct Energy Consumption. Direct energy expenditure per seat-mile available is proportional to the following factors:

- (1) Specific fuel consumption of the engine(s) at the speed at which the vehicle is operating; $(sfc)_v$.
- (2) Equivalent drag-to-gross-weight ratio at the speed of travel: $(D_e/W)_v$ (reverse of the gross-weight-to equivalent-drag ratio: $(W/D_e)_v \equiv V_{kn}W/325 \text{ SHP}$), and
- (3) Gross weight per seat-available; W/S_{av} .

$$(DE/S_{av}NM) \sim sfc_v [1/(W/D_e)_v] (W/S_{av}). \quad (4)$$

This relationship, when referred to as pounds of fuel per seat-available and nautical mile traveled becomes:

$$(DE/S_{av}NM) = sfc_v [1/(W/D_e)_v] (W/S_{av})/325; \text{ lb}/S_{av}NM. \quad (4a)$$

Eqs (4) and (4a) clearly indicate that as far as $DE/S_{av}NM$ is concerned, the following factors tend to minimize its value:

- (1) the lowest sfc for the engine powering the vehicle directly (or for remote powerplants at the source of energy generation);
- (2) maximization of the weight-to-equivalent-drag ratio at the operational speed of the vehicle; and
- (3) the lowest possible ratio of gross weight to the number of seats available.

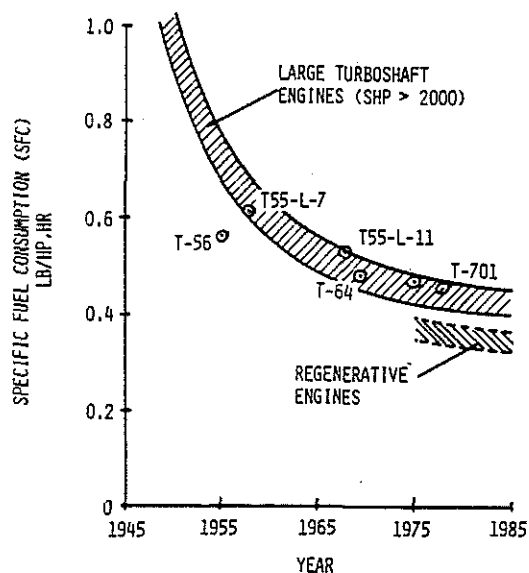
For the vehicle receiving its energy from the outside, maximization of the efficiency of transmitting that energy also becomes an important factor.

TYPE OF ENGINE		sfc; lb/hp/hr
DIESEL	Aircraft (Junkers Jumo)	0.353 – 0.375
	Bus	0.42 – 0.55
	Locomotive	0.37 – 0.39
OTTO	Aircraft	0.42 – 0.48
	Automobile	0.5 – 0.6
TURBO-SHAFT	Aircraft	0.45 – 0.55*

*SEE FIGURE 10

Specific Fuel Consumption. At the current level of technology, there are still noticeable differences in the sfc values for various power generators (Table 1) where diesels represent the lowest levels.

TABLE 1. EXAMPLES OF SPECIFIC FUEL CONSUMPTION



Engines operating at the Otto cycle have inherently higher fuel consumption than diesels, while as far as sfc is concerned, turboshafts probably exhibit the most spectacular progress with the passage of time (Figure 10).

Figure 10. Progress with time in sfc of turboshafts

It can be seen that gas turbines have already reached the same general level of fuel consumption as reciprocating engines and the progress curve has leveled off; however, considerable gains still appear possible through regeneration. Unfortunately, this particular approach would carry considerable weight penalties. Consequently, the merits of regenerative cycles must be evaluated within the broader framework of the total energy economy and economic constraints.

Gross-Weight to Equivalent-Drag Ratio. Helicopter $(W/D_e)_v$ will be discussed later in more detail. At this time, it should be pointed out that its current maximum value of $(W/D_e)_v \approx 5.0$ is much lower than those of other air, ground, or water vehicles (Figure 11). Here, values of W/D_e in excess of 200 can be found for buoyant ships and trains. Dirigibles, being buoyant vehicles, also exhibit high W/D_e levels. However, a rapid decrease of W/D_e with speed of all the buoyant vehicles should be noticed, with the most dramatic drop being exhibited by the buoyant

ships. It should also be emphasized that the D_e 's of trains were determined under no-wind zero-grade conditions. Due to this factor, their actual operational values may be much higher⁶. W/D_e values of surface and ground-effect ships are generally quite low. Automobiles at low speeds of about 40 knots show $W/D_e \approx 30$, which also decreases rapidly with speed.

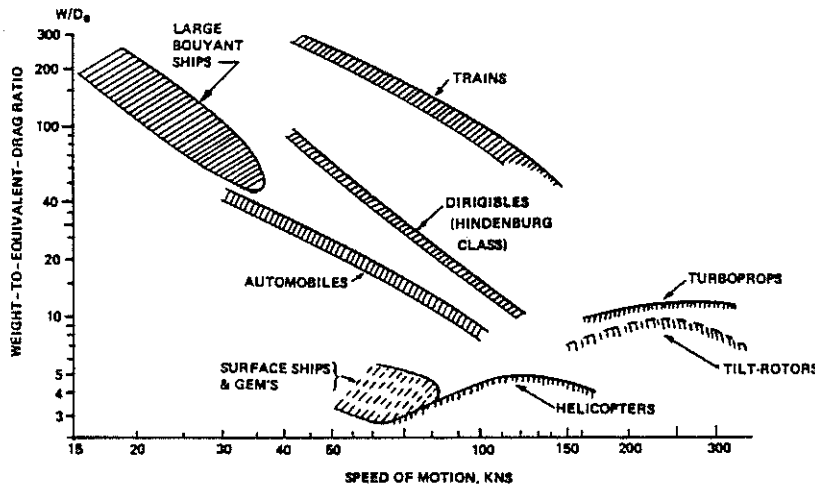


Figure 11. Trends of (W/D_e) values vs speed of motion

Projected W/D_e levels of the tilt-rotor type—although considerably higher than those for helicopters—should still be somewhat inferior to propeller-type fixed-wing aircraft of the corresponding gross-weight class because of the lower propulsive efficiency of the prop-rotor and less favorable weight-to-equivalent flat-plate area ratio.

Gross-Weight per Seat-Available. The range of gross-weight per seat-available (W/S_{av}) is very broad. It can be seen from Table II that for an ocean liner, W/S_{av} may exceed 80,000 pounds, while for a compact car or a ground-effect machine, it may amount to as little as 600 pounds; however, for luxury automobiles, $W/S_{av} \approx 1200$ pounds. Conventional trains—especially those with sleeping cars—show W/S_{av} levels as high as 10,000 pounds. By contrast, this quantity may be as low as 1700 pounds/seat-available for modern trains⁶. In the case of ocean liners, these weight aspects offset the gains resulting from high W/D_e ratios and low sfc levels; thus, energywise, making ships a rather inefficient means of passenger transportation. The differences in the W/S_{av} values also explains why energy consumption per seat-available of luxury and even standard cars is higher than for the compact cars and buses ($W/S_{av} \approx 800$ lb/Sav).

The W/S_{av} values are relatively low for all aircraft; and for helicopters (see Table II and Figure 12), they seem to be within the same range as the fixed-wing aircraft.

An overview of the results of the interplay between all of the above-discussed parameters determining the level of direct energy consumption per seat-mile available can be seen in Table III where the DE/S_{av} NM values for various ground and air vehicles, including a 1960 technology helicopter flying in the NYA operations, are shown as plain (unhatched) bars.

TYPE OF VEHICLE		W/S_{av} , lb/1
AUTOMOTIVE	COMPACT CAR	600 - 750
	LUXURY CAR	1100
	BUS	800
RAIL	CONVENTIONAL TRAIN	4000 - 10,000
	MODERN TRAIN	1700 - 2600
SHIP	OCEAN LINER	50,000 - 84,000
AIRCRAFT	W/B DOMESTIC JET	1100 - 2000
	COMMERCIAL TURBOPROP (DOMESTIC)	850 - 1700
	GENERAL AVIATION FIXED-WING	700 - 1200
	HELICOPTER *	700 - 1100

*see Figure 12

TABLE II. GROSS WEIGHT PER PASSENGER SEAT-AVAILABLE

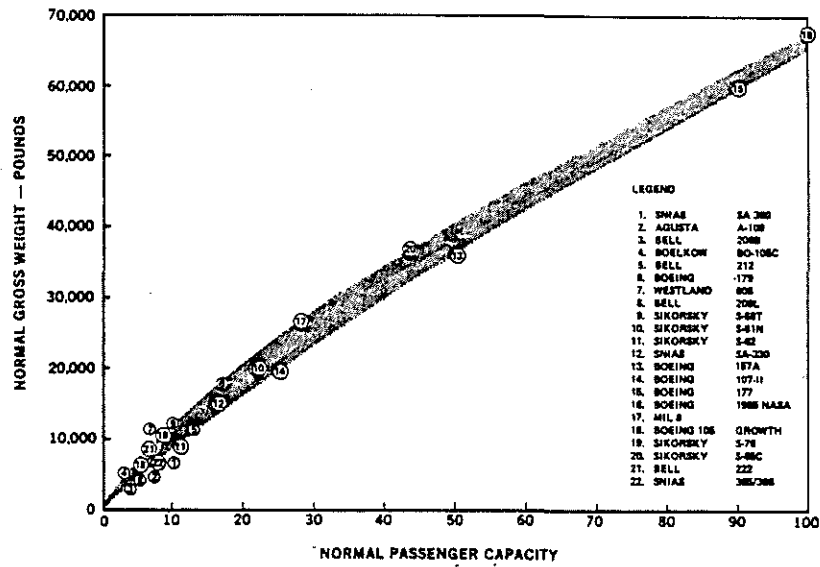


Figure 12. Trend of helicopter gross weight vs number of passenger seats (F. Harris of Boeing Vertol Company)

		DEC/S _{av} NM	IEC/S _{av} NM	TEC/PNM		
		0	2000	4000	6000	8000
		BTU/S _{av} NM, OR BTU/PNM				
AUTOMOBILE	URBAN	TYPE OF VEHICLE				
		STD PASS. CAR IN N.Y. ^{5*}				
		TYPICAL TAXI IN N.Y. ^{5*}	36,700			
		STD PASS. CAR ²	19,200			
	INTER-URBAN	STD CAR ²				
		" CAR @ 55 MPH				
VW "BEETLE" ²						
	VW "MICROBUS" ²					
	NAT'L AVG - ALL CAR OPER					
PUBLIC TRANSPORTATION	URBAN	MASS TRANSIT ²				
		BUS ²				
		PRESENT HELICOPTER ⁷		8,600	16,600	
	INTER-URBAN	BUS ²				
		RAILROAD ²				
AIRPLANE ²				9,600		
	PRESENT HELICOPTER ⁷		7,500	14,400		

*BASED ON POINT-TO-POINT AIR DISTANCE, INCL. EMPTY MILES;
ALL OTHER DATA BASED ON ROAD-TRAVELED DISTANCE

TABLE III. DIRECT AND INDIRECT ENERGY CONSUMPTION PER SEAT-AVAILABLE AND PASSENGER-MILE

Indirect Energy Consumption. It has been mentioned that indirect energy expenditure represents another important factor in the total energy picture. In the case of automobiles, as stated in Reference 2, "Direct consumption of gasoline is only part of the automotive energy picture. Indirectly—to manufacture, sell, maintain, repair, insure, refine petroleum, and build highways—the automobile consumes about 3/5 as much energy as it does directly in gasoline." It is obvious that in a comparison of the indirect energy consumption of helicopters (as well as other aircraft) with automotive vehicles, some charges may be common to both categories. However, the level of energy expenditure for sales, insurance, etc.; for helicopters would probably be lower than for automobiles. Furthermore, energy required for the construction of highways would be much higher than that required for the construction of heliports.

It appears that at least 15 percent of the indirectly consumed energy can be additionally charged to the DE of automotive vehicles to account for highway construction and other indirect expenditures not required for helicopters.

In order to appreciate the importance of the absolute value of energy used each year on highway construction, it is sufficient to realize that in 1970, 10^{15} btu's were used for that purpose². This amounts to about 24.5 million metric tons of diesel fuel per year.

Of course, when this quantity is divided by the total number of automotive vehicles operating on highways and the miles covered by them, it will amount to only 11 percent of the direct energy consumed per available seat-mile. From the point of view of direct energy expended, however, this may create the difference between a shortage and sufficiency of energy in the USA.

Load Factor. Another important contribution to energy expenditure per passenger-nautical mile is the load factor. Where public transportation is concerned, it is usually impossible to adjust the number of seats available to the fluctuations of the traffic flow between rush hours and slack periods. For this reason, the average load factors of urban public transportation is relatively low (see Table IV).

TYPE OF VEHICLE		LOAD FACTOR
URBAN	AUTOMOBILE ²	28% (1.4 PASS./CAR)
	AUTOMOBILE ⁵	24% (1.2 PASS./CAR)
	TAXI ⁵	24% (1.2 PASS./CAR)
	PUBLIC TRANSPORT ²	20%
INTERCITY	AUTOMOBILE ²	48% (2.4 PASS./CAR)
	BUS ²	45%
	RAILROAD ²	35%
	AIRPLANE ²	(50%)

TABLE IV. TYPICAL LOAD FACTORS IN THE USA

indicated in Reference 2, however, statistics obtained for 1970 show a nationwide average factor of 1.9 passengers per car and 1.4 in urban operations. Surveys conducted in New York in 1973-74 (reported in Reference 5) showed an even lower figure of 1.2 passengers per vehicle as a level for the urban load factor. When one looks at helicopters, New York Airways show a load factor of about 50.5 percent.

Additional Mileage. In comparing urban travel by automotive vehicles with that by helicopters, additional mileage resulting from the street traffic structure must be considered. Reference 5 shows that in New York, street routes are about 22 percent longer than the air distance between the points of operation of New York Airways.

Furthermore, it was indicated that quite often, the so-called empty miles should be added and thus the amount of energy expended doubled if the traveler is brought to his destination (say, an air terminal) and then the car returns "empty." In the case of a taxi, some empty miles traveled before a passenger is picked up would also contribute to the actual energy expenditure per PNM (see Figure 9).

Finally, in a comparison of automobiles and helicopters in urban transportation, helicopters may have an additional advantage. Whenever the passenger load is low, they can fill up the space by carrying some cargo, while such an operation is almost unthinkable for the taxi or private automobile.

Total Energy Expenditure. Taking into account all the above-discussed aspects of indirect energy expenditure and load factors, a summary of total energy consumption per passenger mile of various modes of ground transportation is also shown in Table III as hatched bars. This table provides a broad base for energy comparison of helicopters with other modes of transportation. It can be seen that helicopters would not become competitive with either buses or railroads in inter-urban transportation; and especially, with a VW Microbus when it is loaded to full capacity. However, they may become competitive with full-size automobiles in both intra- and inter-urban transportation as long as automobiles operate at their current low-load factors. Of course, in some special situations as in New York City, helicopters may show a better energy economy than private automobiles and taxis (Figure 9).

4. Energy Aspects of Currently Operational Helicopters

In order to gain a deeper insight into the energy situation of helicopters, a study was conducted by J. Davis and myself under NASA-Langley contract⁷. First, attention was focused on currently operational helicopters; i.e., representing the technology level of the early Sixties. Cases of very-short-haul (consisting of a total run of approximately 100 n.mi. with frequent stops), and short-haul (representing inter-city travel up to 200 n.mi.) distances were examined under consistent ground rules.

Very-Short-Haul. As an example of very-short-haul transportation, the routes flown by New York Airways with the S-61L (between John F. Kennedy Airport, LaGuardia, etc.) were examined. It can be seen from Figure 13 that this detailed study confirmed that under the still prevailing modes of operation of automotive vehicles, the

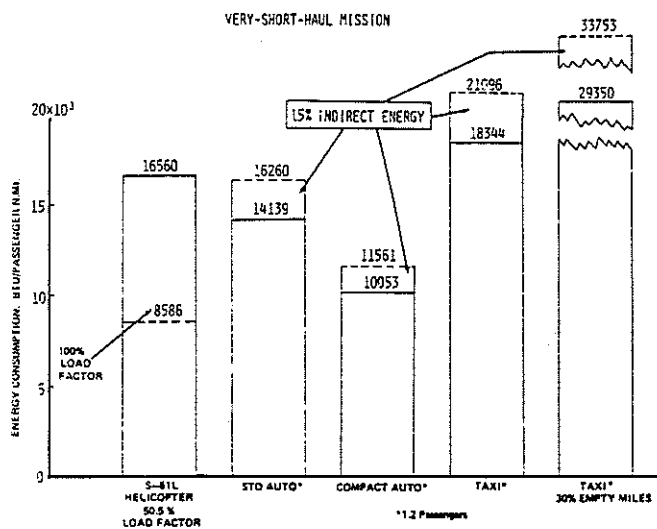


Figure 13 A comparison of energy consumption for very-short-haul missions

helicopter is competitive with private full-size automobiles and taxis. The compact automobile shows some advantage over the helicopter, but if all private automobiles were charged with empty miles as in the case of taxis, then the helicopter would look better in this case also.

It appears, hence, that for very short distances, even helicopters representing early Sixties' technology can definitely be competitive with such means of transportation as private automobiles and taxis which are widely used by a special segment of the population representing businessmen or higher-income class people. However, the helicopter is non-competitive with the mass transportation system and would remain in that position; even assuming that buses, trolleys, and subways continue to operate at the present low average load factor values of twenty percent, while for helicopters, the load factor would increase from the present $LF \approx 50\%$, to $LF \approx 90\%$.

Short-Haul. As an example of short-haul operation, Figure 14 represents an energy comparison for a short-haul mission based on a scenario similar to that between New York and Washington. Trying to make the comparison between helicopters and ground transportation as realistic as possible, it was assumed that automobiles and buses would travel by the shortest route to a superhighway (I-95) linking those two cities and proceed on to their destination. It can be seen from Figure 14 that a helicopter such as the S-61L flying at 60 percent load factor uses much more energy per passenger than either the bus or train. It is also worse than the standard automobile with a typical inter-urban load of 2.2 passengers per vehicle.

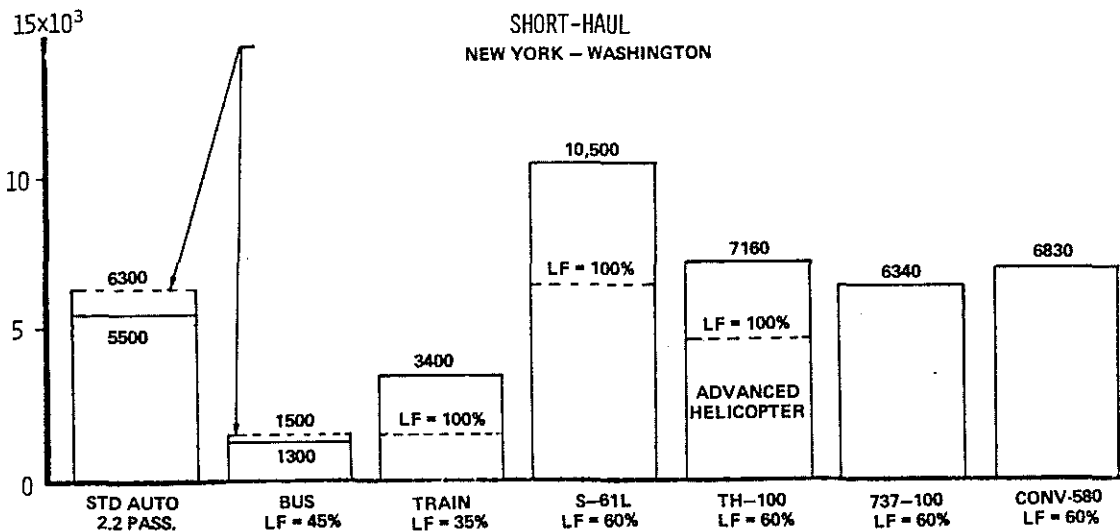


Figure 14. A comparison of energy consumption in short-haul operations (up to 200 n.mi.)

Energy consumption of a helicopter representing advanced technology is also shown in Figure 14. This helicopter, designated the TH-100, was designed to carry 100 passengers and have a gross weight of about 67,000 pounds and a weight empty of about 40,000 pounds (Figure 15). Furthermore, it was assumed that it will incorporate a fly-by-wire control system and that structural weight is reduced by about 25 percent through the use of composite structures⁸, etc. It can be seen from this figure that although the TH-100, energy-wise, would still remain inferior to the bus or train, it becomes almost competitive with such aircraft as the Boeing 737-100 or turbo-props like the Convair 580.



Figure 15. Artist's concept of the TH-100 helicopter

The comparison with fixed-wing aircraft was made under an assumption that there were no unusual delays, either enroute or at takeoff and landing. It may be expected, however, that fixed-wing operational delays have been, and will be, encountered more frequently (especially on heavily traveled routes) than by VTOL aircraft. To appreciate the impact of the delays on energy consumption in short-haul operations, one has to look at Figure 16. Here, it can be seen that 30-minute operational delays on the New York-Washington run can considerably increase consumption per passenger mile for such aircraft as the Boeing 737-100.

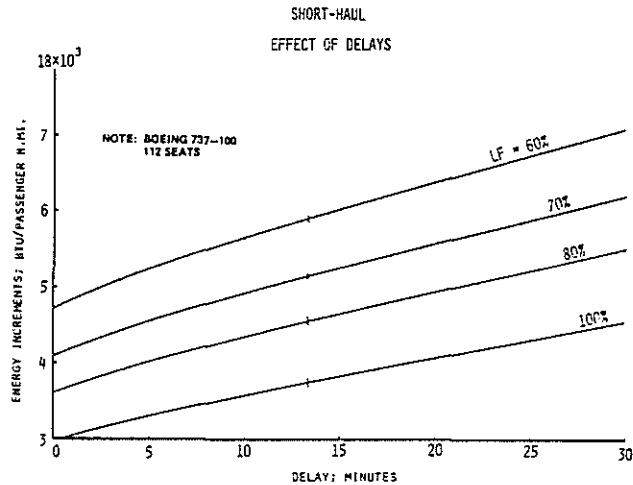


Figure 16. Increase in energy consumption due to enroute delays

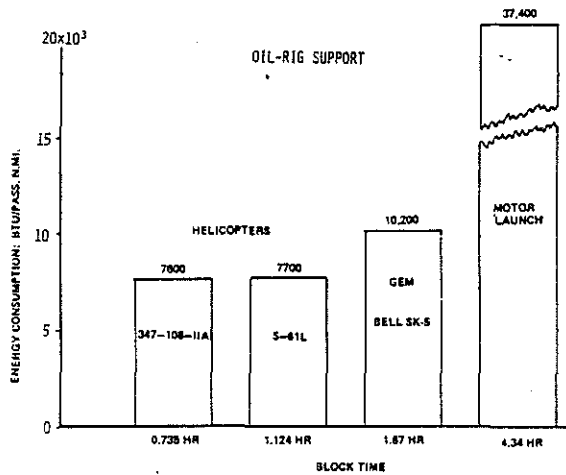


Figure 17 Energy consumption and block time in oil-rig operations

In support of oil rigs, the helicopter appears to have not only a time advantage over other means of transportation, but also has an edge on energy consumption as well. Even helicopters (either tandem or single rotors) representing basically the early Sixties technology level, seem to be superior to ground-effect machines, as exemplified by the Bell SK-5, or surface boats such as a five-passenger motor launch.

5. Ways of Improving Energy Consumption of Helicopters

Upon examining the position of currently operational helicopters in comparison with other transport vehicles from an energy point of view, the question that comes to one's mind is to what extent can helicopters be improved as far as energy consumption is concerned. In order to answer this question and to indicate the potentially best roads leading to an improved energy position, preliminary studies were performed in Reference 7. This was followed by a more detailed analysis by Davis and Rosenstein⁹.

The 100-passenger tandem helicopter developed in Reference 8 and shown previously in Figure 15 was selected as the starting point. On this foundation, baseline aircraft using 1975 technology in the areas of powerplant, rotor efficiency, parasite drag, and structure were sized to a very-short-haul mission of 100 n.mi. and a short-haul mission of 200 n.mi. A systematic parametric analysis was then conducted to assess the impact of technology improvements.

Projections of obtainable technology levels during the 1985 time frame were made and the resources to achieve them were estimated⁹. The best mix of advance technology was selected by evaluating the development cost vs energy consumption per passenger mile. Reductions of $DE/S_{av}NM$ amounting to 36.6% for the very-short and 38.7% for short-haul missions were predicted. Broad aspects of the direct energy consumption per seat-available will be outlined here using selected illustrative examples⁹.

Hovering. Although helicopters represent the most efficient (energy-wise) static thrust generators, further improvements in this respect are both desirable and possible.

In hovering, direct energy consumption (DE_h) can also be computed per seat-available and unit of time (say, one hour). Thus, the dependence of DE_h on the most important rotorcraft characteristics can be expressed by the following proportionality:

$$DE_h \sim SHP sfc/S_{av} \quad (5)$$

but SHP can be expressed in terms of the ideal power required which, neglecting download is $SHP_{id} = W\sqrt{w/2\rho}$ and the overall figure-of-merit FM_{ov} : $SHP = W\sqrt{w/2\rho}/FM_{ov}$. In turn, $FM_{ov} = FM \eta_t$ where FM is the main rotor figure-of-merit and η_t is a coefficient reflecting torque compensation (if present), transmission, and accessory losses. Eq (5) can now be rewritten as follows:

$$DE_h \sim (W/S_{av}) sfc\sqrt{w/2\rho}/FM \eta_t \quad (5a)$$

It can be seen that Eq (5a) has two factors in common with Eq (4); namely, W/S_{av} and sfc , while the figure-of-merit replaces W/D_e in Eq (4). However, in Eq (5a), two additional design parameters appear: disc loading (w) and η_t . Consequently, in the drive to minimize DE_h , they cannot be ignored. Unfortunately, freedom of reducing w is usually limited (at least for constant diameter rotors) by strong constraints of weight, size, and cost. Maximization of η_t is routinely attacked through design and testing efforts, but the most challenging task appears to be that of improving the rotor figure-of-merit.

In order to obtain a better insight into this matter, FM is expressed in the following terms:

$$FM = 1/[k_{ind} + 3.46/\sqrt{\sigma}(\bar{c}_l^{3/2}/\bar{c}_d)] \quad (6)$$

where k_{ind} is the ratio of actual power (RP) to the ideal induced rotor power (RP_{id}), or $k \equiv RP/RP_{id}$; \bar{c}_l is the average rotor-lift coefficient, $\bar{c}_l = 6w/\sigma\rho V_t^2$; \bar{c}_d is the average profile drag coefficient, $\bar{c}_d \equiv 8 RP_{pr}/\sigma\pi R^2 \rho V_t^3$; and σ is the rotor solidity.

The rotor solidity is strongly governed by structural weight considerations; consequently, it cannot be considered as an independent parameter in the process of FM optimization. Assuming in Eq (6) that $\sigma = const$, it becomes clear that k_{ind} should be made as low as possible in order to maximize FM , while $\bar{c}_l^{3/2}/\bar{c}_d$ should be as high as possible. k_{ind} is minimized by attacking the induced power level through such means as blade chord and twist distribution, and then the geometry of the blade arrangement within the rotor and, to some extent, through such airfoil characteristics as prevention of stall, and the steepness of the lift-curve slope.

With respect to the second term in the square brackets of Eq (6), the task would consist of the development of "fixed" airfoils showing the highest possible $\bar{c}_l^{3/2}/\bar{c}_d$ levels, or trying to improve this ratio in hover through geometric variation of the airfoil shape, and by such means as boundary-layer or circulation control.

Assuming $\sigma = 0.10$ as typical of contemporary designs, Figure 18 was prepared in order to give some idea of the combinations of k_{ind} 's and $\bar{c}_l^{3/2}/\bar{c}_d$'s required to make the value of the figure-of-merit higher than $FM \approx 0.7$; although at the present time this value is considered to be good.

In addition, examples of $(\bar{c}_l^{3/2}/\bar{c}_d)_{max}$, which is obtainable with the symmetrical (0012) and cambered (V23010-1.58) airfoils, are also noted on this figure. The two higher values are based on wind-tunnel tests of smooth models¹⁰, while the lowest one may be considered as representative of symmetrical airfoils of blades with surfaces roughened by erosion as encountered in actual operations.

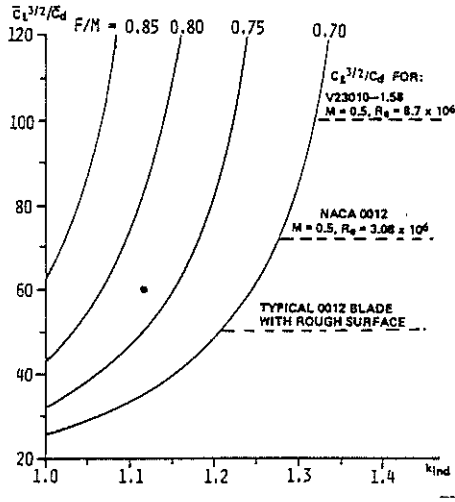


Figure 18. Required $(c_d^{3/2}/c_d)$ vs k_{ind} for given FM values

Horizontal Flight. Energy consumption in horizontal flight is the Achilles heel of helicopters. Consequently, improvements in this domain should merit special attention. From the designer's point of view, the most important task is to reduce the energy consumption per seat-mile available ($DE/S_{av}NM$). This is proportional to the product of three factors: sfc , W/S_{av} , and $1/(W/D_e)$. Hence, the reduction of $DE/S_{av}NM$ to some new desired level (say, one-half of the present value) can, in principle, be obtained by appropriately reducing any one of the above factors. The same goal can also be achieved by reducing any two, or all three, factors to such an extent that their product becomes equal to the desired figure.

Intuitively, one would feel that the largest advances should be made by following the paths of least resistance. This means that effort should be concentrated on those factors where the largest relative gains are possible with the least penalty (e.g., cost).

One may imagine that once a departure is made from the current state-of-the-art, then the "cost" associated with the desired progress would increase more rapidly than would be proportional to the achieved gains. Furthermore, when goals of improvement are too ambitious, one may reach such a stage of diminishing returns that even extremely large expenditures of money, time, and effort would produce only very limited, or no, gains at all. In such a case, the $cost = f(gains)$ curve becomes asymptotic to the ordinate representing cost.

To obtain some insight into the possibilities of gains and associated costs for the three factors determining the $DE/S_{av}NM$ level, each of them is briefly reviewed.

Specific Fuel Consumption. Further improvements in the specific fuel consumption without regeneration (Figure 10) can be cited as an example of approaching the "progress barrier." This seems to indicate that immediate efforts should be more aggressively directed toward (W/S_{av}) reduction and (W/D_e) increases than toward lowering sfc at rated power. It should be realized, however, that even without further improvement of sfc at rated power, some practical gains in helicopter specific fuel consumption are possible in cruise, where the powerplants usually

It is obvious that $c_d^{3/2}/c_d$ values for the blade as a whole should be expected to be lower than the $(c_d^{3/2}/c_d)_{max}$ value obtained from wind-tunnel tests of a smooth model of a particular airfoil section.

It is also apparent from this figure that once $c_d^{3/2}/c_d$ becomes higher than 100, the FM curves become less sensitive to further improvements in the $c_d^{3/2}/c_d$ levels, but remain sensitive to the k_{ind} . It appears, hence that from the FM point of view, airfoil development has already reached a level where further improvements in their characteristics would contribute little to an improvement in the rotor figure-of-merit. Consequently, attention should be concentrated toward minimization of the induced power. It is also clear from Figure 18 that achieving $FM \approx 0.83$ would not be an easy task for $c_d^{3/2}/c_d \approx 100$ as it would require $k_{ind} \approx 1.1$ only. However, Davis and Rosenstein⁹ came to the conclusion that $FM \approx 0.83$ is possible, but the potential gains would be accompanied by corresponding penalties as represented by the development cost which increases sharply when $FM \rightarrow 0.80$ (Figure 19).

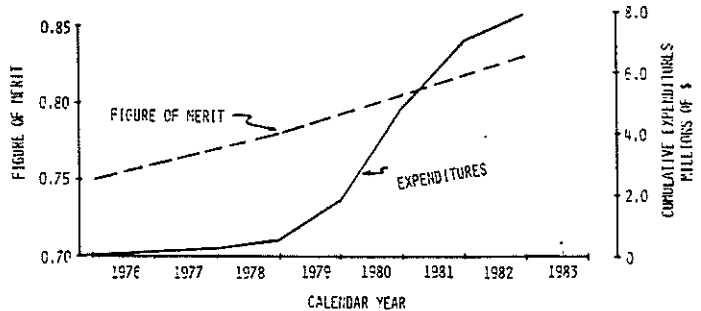


Figure 19. Gains and expenditures for Figure-of-Merit

operate at a fraction of the rated power. Shifting sfc_{min} in the direction of partial power settings could represent a considerable contribution to the reduction of $DE/S_{av} NM$. Finally, long-range plans should not neglect the possibility of a quantum jump in sfc reduction through regeneration.

Gross-Weight per Seat-Available. The design gross weight W can be expressed as the following sum:

$$W = W_e + W_p + W_f + W_{fix} \quad (7)$$

where W_e is the weight empty; W_p is the weight of payload which, for passenger transport, can be expressed as a product of the number of seats-available times the design passenger weight (W_{pas}): $W_p = S_{av} W_{pas}$; W_f is the fuel weight; and W_{fix} is the fixed weight (crew and trapped liquids). W/S_{av} can now be expressed as

$$W/S_{av} = W_{pas} / \{ 1 - [(W_e/W) + (W_f/W) + (W_{fix}/W)] \}. \quad (8)$$

It can be seen from Eq (8) that the (W/S_{av}) values are actually influenced by all three of the weight ratios appearing in the square brackets. However, just to obtain a trend of the W/S_{av} variation vs the relative weight-empty ratio (W_e/W), it will be assumed that the remaining two ratios are fixed at values typical for a helicopter such as the 100-passenger TH-100 designed using 1975 technology and serving as a compromise between the very-short-haul and short-haul missions⁹: $W_f/W = 0.097$; $W_{fix}/W = 0.023$; $W_{pas} = 180$ pounds; and $W_e/W = 0.666$. These assumptions would result in $(W/S_{av})_0 = 840$ pounds. The influence of reducing W_e/W below its starting value can be judged

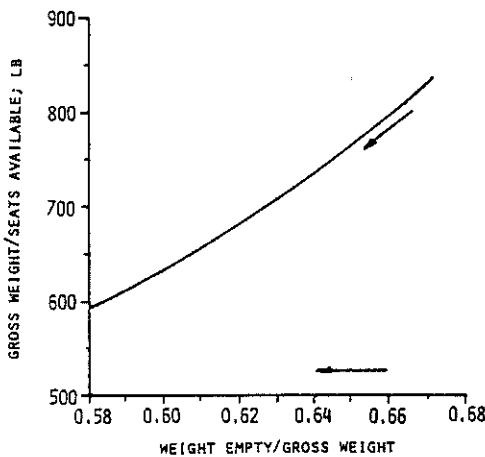


Figure 20. Influence of W_e/W on W/S_{av}

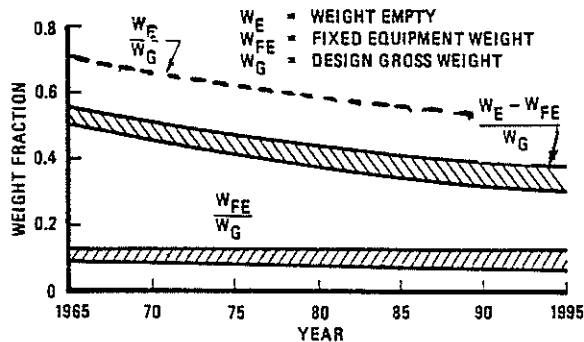


Figure 21. Relative weight trends

from Figure 20. The past statistical, as well as future, trends of the weight ratios is reproduced in Figure 21¹¹. The W_e/W point for 1975 used in the original (W/S_{av}) estimate which appears above the corresponding trade line may be explained by the fact that this figure was based on both military and civilian designs. However, the slope of the past variation of W_e/W is correct. The question is whether the future W_e/W trend should follow the predicted line, or, because of the importance of the W_e/W ratio for the energy posture of helicopters, concentrated effort should be made to lower these ratios. It is more probable that earnest efforts will be made to improve these predicted trends. This could be done through application of high-strength materials, especially those based on carbon, boron, and glass fibers.

Weight-to-Equivalent-Drag Ratio. The problem of increasing the (W/D_e) ratio of helicopters depends on the number of design parameters influencing the (W/D_e) values. Here, a rather cursory approach will be outlined considering the influence of two "super parameters." — the rotor-lift to equivalent-drag ratio $(L/D_{er}) \approx (W/D_{er})$; and weight-to-equivalent parasite-drag ratio (W/D_{epar}) , where $D_{epar} = D_{par}/\eta_t$.

At a given speed of flight V , the inverse of the W/D_e of the helicopter as a whole can be expressed as follows:

$$\frac{1}{W/D_e} = \frac{1}{W/D_{e_r}} + \frac{1}{W/D_{e_{par}}} \quad (9)$$

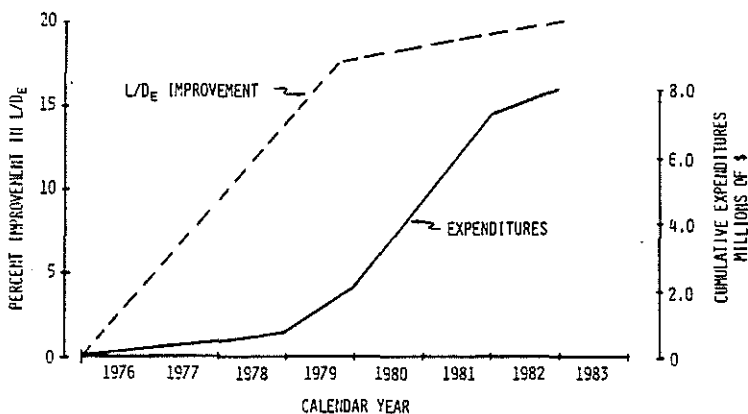


Figure 22. Gains and expenditures for rotor L/D_e

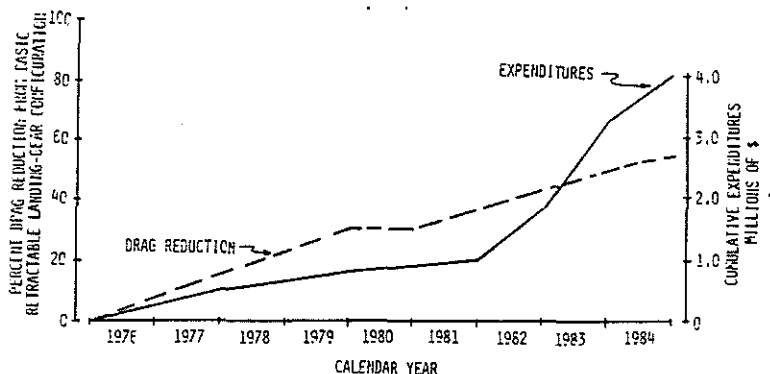


Figure 23. Gains and expenditures in possible drag reduction

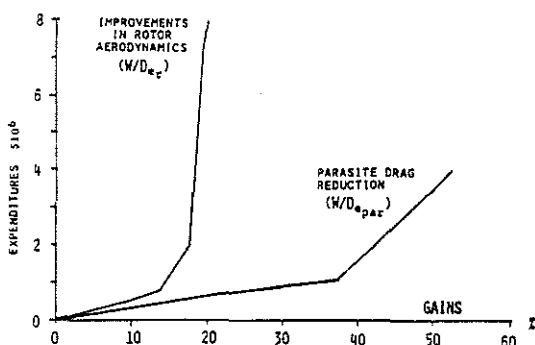


Figure 24. Expenditures vs relative gains

Figures 22 and 23⁹ are shown as examples of gains and penalties (cost) associated with increasing W/D_{e_r} and reducing parasite drag, which is synonymous with improving $W/D_{e_{par}}$. In order to provide a better insight into the cost associated with various levels of relative gains, these figures were replotted as shown in Figure 24. It can be clearly seen in this figure that (1) a sharp upturn in expenditures (penalties) occurs after reaching some level of progress, and (2) a much greater level of progress can be shown in parasite drag reduction (increase in $W/D_{e_{par}}$) than in the rotor W/D_{e_r} improvements for the same amount of money spent.

At this point, one may question how technical efforts should be directed; i.e., how much emphasis should be placed on rotor aerodynamics and how much on drag reduction, if some desired improvement in the overall W/D_e of a helicopter must be achieved at a minimum cost.

The following simple graphical optimization is outlined to give some idea of how this question may be answered.

Minimization of the (W/D_e) Improvement Cost. Let it be assumed that at some flight speed, V , the

inverse of the lift-to-drag ratio of the baseline helicopter is $\Sigma_o \equiv 1/(W/D_e)_o$, while the corresponding inverses of $(W/D_{e_r})_o$ and $(W/D_{e_{par}})_o$ respectively, are Σ_{r_o} and Σ_{par_o} . Eq (9) can now be rewritten as follows:

$$\Sigma_o = \Sigma_{r_o} + \Sigma_{par_o} \quad (9a)$$

The task consists of reducing Σ_o by a factor $\lambda < 1.0$ by decreasing Σ_{r_o} to a new value $\lambda_r \Sigma_{r_o}$, and Σ_{par_o} to $\lambda_{par} \Sigma_{par_o}$ in such a way that the cost of this operation (equivalent to an increase of $(W/D_e)_o$ by a factor $1/\lambda$) is minimal. For the new desired value of the inverse of the W/D_e of the helicopter at the same speed, Eq (9a) becomes:

$$\lambda \Sigma_o = \lambda_r \Sigma_{r_o} + \lambda_{par} \Sigma_{par_o}. \quad (10)$$

It can be seen from Eq (10) that $\lambda\Sigma_o$, in principle, can be obtained—if the goal is not too high—through the reduction of either λ_r or λ_{par} alone, while the other factor remains equal to 1. It can also be attained by making both $\lambda_r < 1.0$ and $\lambda_{par} < 1.0$. By solving Eq (10) for λ_r , a direct relationship between λ_r and λ_{par} is obtained:

$$\lambda_r = (\lambda\Sigma_o - \lambda_{par}\Sigma_{par_o})/\Sigma_{r_o}. \quad (11)$$

Now, various values of λ_{par} can be assumed, and the corresponding λ_r 's can be calculated from Eq (11). The accumulative cost of achieving each pair of the λ_r and λ_{par} values can be computed from a graph such as the one shown here in Figure 24. From such a graph one could find the combination of λ_r and λ_{par} at which the total cost becomes a minimum; thus indicating the area of improvement at which efforts should be directed—in this case, rotor aerodynamics vs parasite drag—in order to achieve the desired level of W/D_e at a particular speed of flight.

As an illustration of this procedure, the following values, which may be considered as typical for the early 1970 technology level and speed of flight $V \approx 165$ knots, are assumed: $W/D_{e_o} = 4.3$; i.e., $\Sigma_o = 0.23$, $\Sigma_{r_o} = 0.10$, and $\Sigma_{par_o} = 0.13$. Let it also be assumed that it is desired to reduce Σ_o by the factor $\lambda = 0.7$, which is equivalent to an increase of the helicopter weight-to-equivalent-drag ratio to $W/D_e = 6.25$.

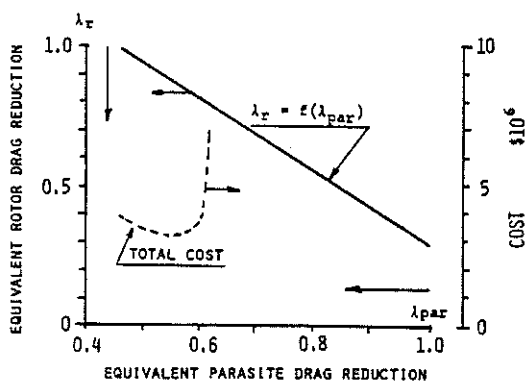


Figure 25. Example of cost optimization

The $\lambda_r = f(\lambda_{par})$ relationship (computed from Eq (11)), as well as the cumulative cost corresponding to various combinations of λ_r and λ_{par} required to achieve the desired goal, is shown in Figure 25.

It can be seen from this figure that the cost is minimized when efforts are chiefly directed toward parasite drag reduction to the level of 55 percent of its original value ($\lambda_{par} \approx 0.55$), while the equivalent drag of the rotor is reduced to about 88 percent of its original value ($\lambda_r \approx 0.88$); i.e., L/D_{e_r} increased by about 13.5 percent.

Figures 24 and 25 tend to indicate that the most cost effective way toward moderate improvements of the W/D_e levels of helicopters should be through parasite drag reduction. Of the many areas where parasite drag reduction is needed, the hub drag which amounts to about 40 percent of the total¹² represents the most important target for improvement. For a long time, this

looked like an almost impossible task because of the mechanical complexity of the fully articulated rotors with hinged blades. Fortunately, the present hingeless and future bearingless rotor configurations open the door for considerable progress in that domain.

It should be remembered, however, that even complete elimination of the parasite drag would still not make the W/D_e of the helicopter higher than the L/D_e of the rotor itself. This, of course, means that in spite of the fact that the road toward improvements in the L/D_e of the rotor appears difficult and costly, it cannot be neglected if, in the long run, one wants to make the W/D_e of helicopters more competitive with other transport vehicles.

Cost Minimization for DE/S_{av} NM Gains. Possibilities and problems associated with improvement of each of the three main factors governing the DE/S_{av} NM level have just been discussed. Now we will take a look at a method for providing a guide for a distribution of efforts between sfc , W/D_e , and W/S_{av} which would result in the minimization of the overall penalties (cost) of reducing DE/S_{av} NM to a new desired level.

Trend curves of gains and costs similar to that shown in Figures 22-24 should be established for sfc , W/D_e and W/S_{av} . This can be done either through engineering studies (e.g., Reference 9), or simply by gathering and averaging the educated guesses of the experts. For the sake of simplicity, it will be assumed that the predicted trends can be approximated by second-degree parabolae of the $y = ax^2$ type, where the value of the coefficient a would reflect the steepness of the cost increase vs relative progress. The advantages of this parabolic approximation stem from the fact that in many optimization tasks, this approach greatly simplifies the process of finding the optimum values of gains. Obviously, other (sometimes more fitting) functions can be used to approximate the predicted cost vs gains relationship, but finding the optimum would probably require more computational effort.

Returning to the problem of cost minimization for the $DE/S_{av} NM$ reduction, it will be assumed that the new desired value of $DE/S_{av} NM$ is $\lambda(DE/S_{av} NM)_0$, where $\lambda < 1.0$ is the reduction factor and subscript zero denotes the baseline level. This total reduction, denoted by λ , will be accomplished through the decrement of the particular factors in the following way: $sfc = \lambda_s sfc_0$; $W/S_{av} = \lambda_w (W/S_{av})_0$; and $D_e/W = \lambda_d (D_e/W)_0 \equiv \lambda_d [1/(W/D_e)_0]$, where λ_s , λ_w , and λ_d respectively, are the reduction factors for sfc , W/S_{av} , and D_e/W . Values of these factors will be such that

$$\lambda = \lambda_s \lambda_w \lambda_d. \quad (12)$$

The cost or other penalties associated with the progress in sfc , W/S_{av} , and W/D_e can be expressed as

$$y_s = a_s (1 - \lambda_s)^2 \quad (13)$$

$$y_w = a_w (1 - \lambda_w)^2 \quad (14)$$

$$y_d = a_d (1 - \lambda_d)^2; \quad (15)$$

thus, the total cost would become

$$y_{tot} = y_s + y_w + y_d. \quad (16)$$

The task consists of selecting λ_s , λ_w , and λ_d in such a way that $y_{tot} = \min$. In this case, the desired optimum values of λ_s , λ_w , and λ_d can be found through elementary procedures of finding an extremum of a function of several variables.

To provide some feeling regarding the optimization process, it will be assumed that it is desired to reduce $DE/S_{av} NM$ to 50 percent of its baseline level; i.e., $\lambda = 0.5$.

As the first example, let us make the rather improbable assumption that a given relative (percentile) reduction of sfc , W/S_{av} , and D_e/W each requires exactly the same amount of effort (cost). This means that $a_s = a_w = a_d$. Under this assumption, the 50 percent reduction of $DE/S_{av} NM$ at a minimum cost would require that all three factors must be reduced equally through $\lambda_{s,opt} = \lambda_{w,opt} = \lambda_{d,opt} = 0.794$. By adhering to this policy, the total cost would amount to approximately 51 percent of that encountered in a single-factor approach (Figure 26). From the point of view of technical policy, the result would imply that efforts should be equally divided between engine developments, sfc ; structures, W/S_{av} ; and aerodynamics, D_e/W .

However, a more realistic assumption would stipulate that an equal relative reduction of W/S_{av} and D_e/W would require approximately the same amount of effort (cost), while the same percentile progress in sfc would be as much as, say, three times more costly. This would mean that $a_w = a_d$, while $a_s = 3a_w = 3a_d$.

Under these assumptions, the optimum individual reduction factors would be as follows: $\lambda_{w,opt} = \lambda_{d,opt} = 0.725$; and $\lambda_{s,opt} = 0.95$.

The magnitude of reduction in penalties (cost) resulting from the above multi-factor approaches versus that representing a reduction of either W/S_{av} or D_e/W alone, can be appreciated from Figure 27.

At this point, it should be stressed that since the $a_s = 3a_w = 3a_d$ approximation was considered as being more realistic, conclusions reached from the solution shown in Figure 27 may be considered as technically sound. It may be stated, hence, that for a moderate reduction (no more than 50 percent of the present values) of $DE/S_{av} NM$,

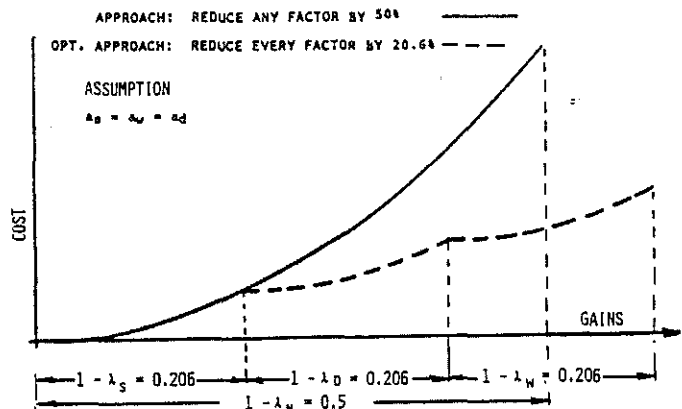


Figure 26. Example of single-factor vs optimal approach

vigorous efforts should be directed equally toward reduction of W/S_{av} and D_e/W with the aim of decreasing each to about 72 percent of the present values. By contrast, in the area of sfc , progress should be restricted to a modest 4 percent reduction from its current level. This obviously means that the main concentration should be focused toward improved structural and aerodynamic efficiencies of helicopters.

The above-discussed procedure represents a very simplistic optimization process. There are, of course, many more sophisticated ones. Regardless of the method used in the minimization of the total expenditures associated with reduction of energy consumption, one should not lose sight of possible conflicts with economic, safety, and flying qualities requirements. Figures 28 and 29⁹ are shown to illustrate how a set of design parameters optimizing energy consumption of a helicopter may lead to a configuration less favorable as far as direct operating cost is concerned.

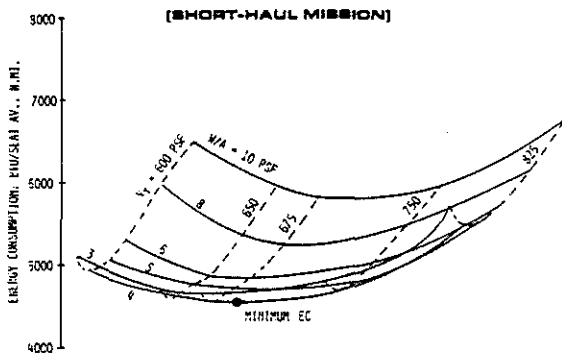


Figure 28. Optimization of energy consumption

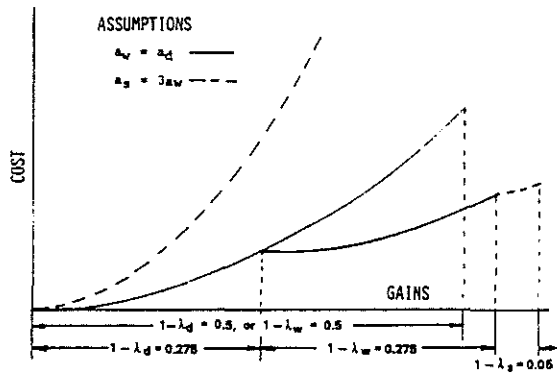


Figure 27. Another Example of single-factor vs optimal approach

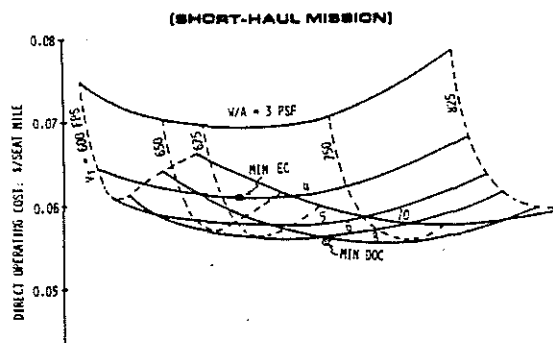


Figure 29. Optimization of direct operating cost

6. Concluding Remarks

1. Similar to all other modes of transportation, energy consumption of VTOL aircraft in general, and helicopters in particular, now become one of the most important factors for their future numerical growth and acquisition of new fields of application.
2. Although the present position of helicopters in regard to energy consumption per passenger-mile is generally inferior to that of many other types of vehicles, their unique hovering and operational capabilities—in many applications—make them either almost, or actually competitive energy-wise.
3. Energy consumption per seat-mile available of helicopters can be greatly reduced (to 50 percent, or even less) through (a) higher aerodynamic cleanness (reduction of D_e/W), (b) structural weight reduction (lower W/S_{av}), and (c) improvement in powerplant characteristics (lower sfc and specific engine weights). However, in order to achieve the greatest progress within limited resources, proper optimization techniques charting the most "profitable" paths and indicating the optimum level of effort for all factors contributing to the reduction of energy consumption should be used.
4. Energy aspects of rotary-wing or more generally, of all VTOL aircraft should be considered within a larger framework of the complete national transportation system with the aim of reducing the total (direct and indirect) energy consumption of this system.

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