Rotorcraft Cost Too Much.

Franklin D. Harris*
F. D. Harris & Associates
Fountain Hills, Arizona

Dr. Michael P. Scully
Senior Research Engineer
Aeroflightdynamics Directorate
Ames Research Center, Moffett Field, Calif.

Abstract

The rotorcraft industry is pricing itself right out of the commercial transportation marketplace. This is illustrated by helicopter prices that have inflated significantly faster than consumer product prices and by helicopter productivity per dollar that decreases with increased purchase price. Specifically, inflation in helicopter purchase price has significantly exceeded the U. S. consumer price index since 1980. When measured in ton–knots, productivity per 1994 purchase price dollar has diminished with increased size, cruise speed and added features. In sharp contrast, the propeller driven, fixed wing airliner industry has not followed the rotorcraft industry in this unsatisfactory trend.

Purchase price analysis of 120 helicopters using linear regression statistical analysis has yielded a price estimating equation. This equation shows helicopter prices are more sensitive to installed power than to weight empty. Inclusion of 126 General Aviation aircraft and 163 airliners in the regression analysis has shown that price is linearly dependent on a size factor. This pseudo, universal size factor contains both weight empty *and* total engine(s) rated horsepower design parameters. At equal size factor, helicopters are priced about 50 percent higher than airplanes in the commercial marketplace. This appears to be the premium for vertical takeoff and landing capability. Preliminary price and performance data for two emerging tiltrotors show that the helicopter's low cruise speed problem has been solved. The rotorcraft industry can now expand into the airliner marketplace if it can substantially reduce the premium price for VTOL.

The traditional minimum weight empty design approach results in excessive installed power due to high disc loading. The design approach has been necessary to meet military requirements such as fitting helicopters inside an Air Force C-130 and operating tiltrotors from a Navy ship. This military oriented design approach is wrong for commercial products. The price estimating relationship developed shows that designing for minimum weight empty does not equate to minimum helicopter purchase price for the commercial operator. Continuing a military oriented design approach for advanced commercial products such as civil tiltrotors is not recommended.

Introduction

In contrast to the rotorcraft industry's outstanding support of world military requirements over the last five decades, our industry's track record in the commercial world leaves a lot to be desired. When Cierva introduced his Autogiro in 1926 it can be reasonably argued that the rotorcraft industry had a viable alternate to the then virtually undeveloped commercial airplane. Since that milestone, it has been, comparatively speaking, all downhill. The public seems to

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* Formerly V. P., LHX Engineering for the Bell Helicopter Textron/McDonnell Aircraft Co. SuperTeam

perceive helicopters today much as they did the aeroplane before Charles Lindbergh “jolted [the American public] out of its apathy towards aviation on 20 – 21 May 1927.” (Ref. 1, page 55.) No derivative of the Autogiro or the helicopter (i.e., compounding) has been able to gain parity with airplane productivity per purchase price or airplane total operating costs. During the last decade helicopter purchase prices (see Figure 1), spare parts prices and operating costs have risen sharply.

Perhaps the most discouraging trend faced by commercial operators, both small and large, has been the inflation in helicopter purchase price (Refs. 2 and 3). This inflation has been far in excess of the U. S. Consumer Price Index. From a military point of view, the U.S. Department of Defense has also seen the cost of buying rotorcraft rise substantially. This less than satisfactory situation for the DoD was graphically displayed by Augustine (Ref. 4, Fig. 11). Augustine’s figure is captioned “The slope of the unit cost vs. time curve for rotary–wing aircraft is the same as for fixed–wing aircraft, albeit getting off to a somewhat belated start.” The magnitude of this growing purchase price problem is quantified by Figure 1.

Figure 1 shows that the price an operator must pay for a helicopter has been inflating at a faster rate than either of two recognized U. S. Government price indices. In the commercial transportation world, inflation to a consumer (i.e. ticket price) has, as given by Ref. 5 in table No. 745, approximately followed the U. S. Consumer Price Index. Such a divergence between helicopter purchase price and the income that can be derived by using the helicopter, makes an operator’s job all the more difficult.

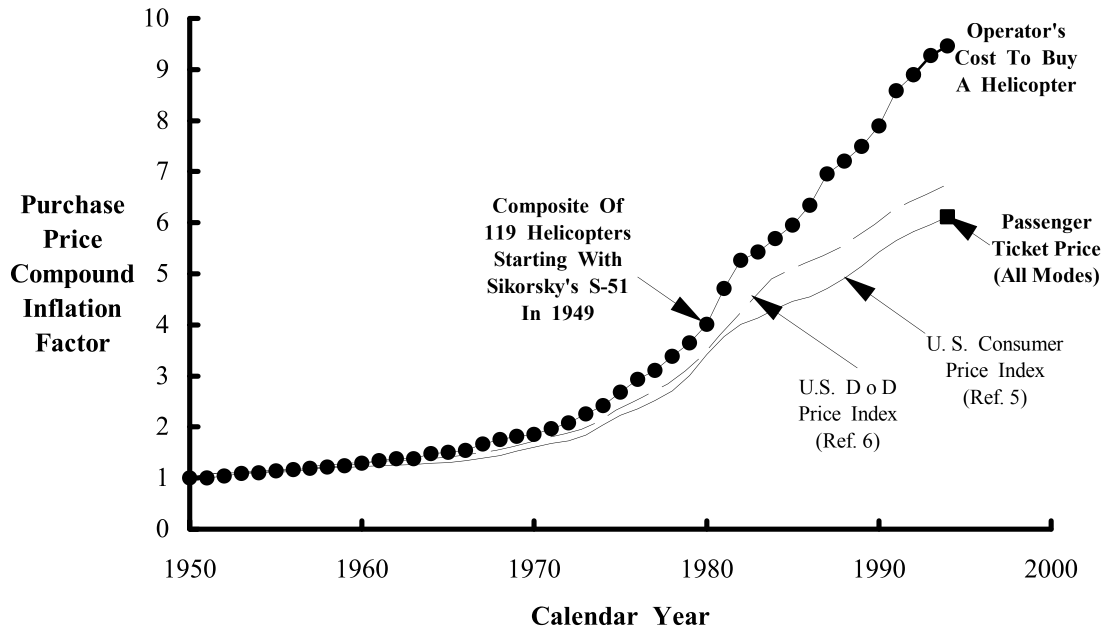

Fig. 1. The rotorcraft industry is pricing itself right out of the transportation marketplace.

A commercial operator’s ability to make a profit is driven more by total operating costs than by helicopter purchase price alone. However, a recent rotorcraft economics workshop, conducted by NASA Ames in May 1996, provided several papers (Ref. 7) concluding that items driven by helicopter price (financing, depreciation, insurance, spare parts) account for more than 40 percent of total operating costs. Therefore, examining what drives helicopter purchase price is one step closer to understanding profitability in the rotorcraft world.

This paper quantifies helicopter purchase price in terms of design variables. A similar quantification is given for fixed wing aircraft for comparison purposes. Reasons for why airplanes have bested helicopters in terms of productivity per purchase price dollar are then suggested. The implications of applying a military oriented design approach to commercial rotorcraft products are discussed. Recommendations that will help the rotorcraft industry create more competitive commercial products are offered. All data supporting this paper can be found tabulated in Ref. 8.

Productivity Per "Buck"

Helicopters and propeller driven airplanes differ substantially in productivity versus purchase price trends. These contrasting historical trends are shown in Figure 2. [The definition of productivity used here is useful load in U.S. tons times economical cruise speed in knots. Useful load is taken as the sum of payload (i.e., passenger and cargo) plus fuel. Purchase price of a helicopter with standard equipment is called base price. The base price plus optional equipment is equipped price. Keep in mind that safety, comfort, reliability, TBO increases and other improvements *are not reflected* in this simple productivity measure. No attempt is made to examine manufacturer cost because this information is not generally available. Examining productivity per total operating cost is beyond the scope and intent of this paper.]

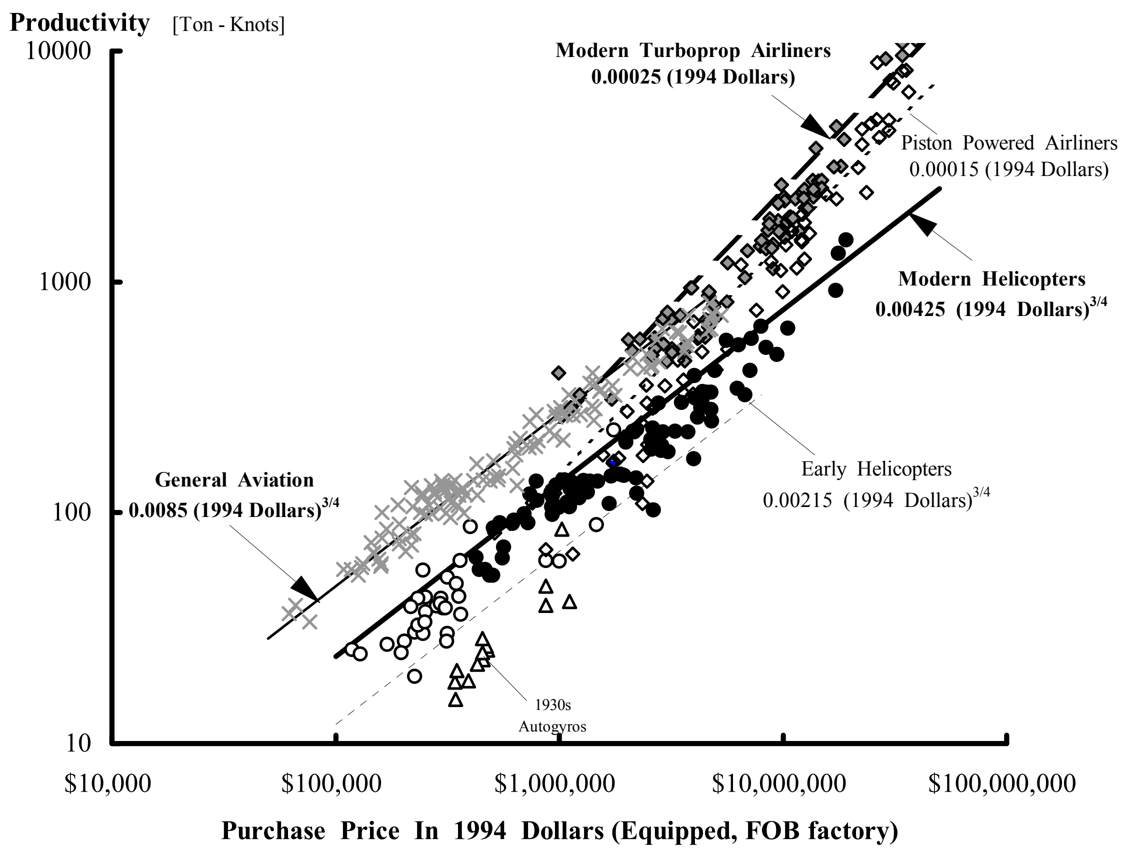

Fig. 2. Propeller driven, fixed wing aircraft have enjoyed significant productivity and price advantages over helicopters. (Open symbols are piston powered, solid are turbine.)

The helicopter industry offers users increased productivity if they will pay more as Figure 2 shows. The productivity that a 1994 dollar will buy is described by the simple, empirical equation

$$\text{PRODUCTIVITY (ton - knots)} = 0.00425\ (1994\ \text{Dollars})^{0.75} \qquad (1)$$

This equation is the dark solid line near the top of the open and solid circle symbols on Figure 2 and represents current technology and business pricing offered by the rotorcraft industry. The helicopter's starting technology is measured by the dotted line lying below most of the circle symbols on Figure 2 and approximated by the equation

$$\text{PRODUCTIVITY (ton - knots)} = 0.00215\ (1994\ \text{Dollars})^{0.75} \qquad (2)$$

These measures of the equipped helicopter's place in the transportation world show that our industry has doubled productivity per 1994 dollar since our start with the Bell 47 and Sikorsky S-51. This progress is reflected by the constant 0.00215 increasing to 0.00425 in the above equations. The S-51 offered 1,500 pounds of useful load and 70 to 80 knot cruise speed for about $114,000 in 1953. Escalating 1953 dollars to 1994 dollars, following Figure 1, would make the S-51's price today approximately $1.0 million. Today's helicopter has almost twice the cruise speed for the same useful load which accounts in large measure for the increased productivity.

The rotorcraft industry justifiably takes pride in maturing the helicopter over the last five decades. However, a fixed wing advocate might point out that today's modern gas turbine helicopter is about on par with such pre World War II airliners as the Ford Tri – motor and the legendary Douglas DC-3. Of course, this simple measure of productivity ignores (1) the helicopter's unique ability to operate from very small vertiports and (2) the airliner's need for long runways and dedicated terminal area airspace.

The downside to our efforts in maturing the helicopter is that productivity per "buck" has gone down as we have offered larger and more sophisticated products. This fact is demonstrated with a little simple math as follows:

$$\frac{\text{Productivity}}{\text{1994 Dollar}} = \frac{0.00425\ (\text{1994 Dollar})^{0.75}}{\text{1994 Dollar}} = \frac{0.00425}{(\text{1994 Dollar})^{1/4}} \approx \frac{1}{(\text{Size}\ \&\ \text{Features})^{1/4}} \qquad (3)$$

This formula says that the productivity per "buck" of a $1,000,000 equipped helicopter is about 134 ton–knots per $1M. However, for a $10,000,000 equipped helicopter, the productivity per "buck" goes down to 76 ton–knots per $1M. This adverse trend may well explain the slow sales of large, sophisticated, fully equipped helicopters.

This helicopter productivity per "buck" trend, as Figure 2 shows, parallels General Aviation (GA) evolution, not the airliner trend. The reason both helicopter and GA aircraft have this adverse trend (relative to both past and present airliners) will be discussed later. Roughly speaking, at equal price, GA aircraft offer *twice* the productivity available from helicopters. Despite this disadvantage, a Vertical Takeoff and Landing (VTOL) niche has apparently been satisfied by the helicopter during the past five decades. Unfortunately, several attempts by the rotorcraft industry to offer a competitive commuter airliner have failed. Therefore, there is little evidence to date showing a transition by rotorcraft to the more favorable productivity per "buck" characteristic of airliners. If the rotorcraft industry seriously intends to offer its VTOL feature to the airliner market, Figure 2 suggests that the historical, adverse, productivity per "buck" trend must improve.

Now consider what the propeller driven, fixed wing airliner industry has accomplished in seven to eight decades. This side of the business has succeeded in (1) perfecting the piston engine, propeller driven commercial airliner, (2) weathering the 1950s transition period to swept wing, jet aircraft, (3) maintaining a technology and manufacturing base while the airlines abdicated unprofitable shorthaul routes, (4) picking up where they left off as airlines again saw the need for propeller driven designs, (5) incorporating better engines, improved propellers and other advanced technologies and (6) applying very cost conscious, aggressive business practices.

The productivity versus purchase price trend for equipped, propeller driven airliners using either piston or gas turbine engines is illustrated by Figure 2. These airliner trends can also be summarized with simple, empirical equations. For modern, equipped, turboprop airliners,

$$\text{PRODUCTIVITY (ton - knots)} = 0.00025\ (1994\ \text{Dollars})^{1.0} \tag{4}$$

This equation is graphically displayed as the dark, long dashed line above most solid, diamond symbols shown on Figure 2. This estimate measures, primarily, turboprop technology and competitive business pricing offered by a growing number of airplane manufacturers. There are, unfortunately, very few United States manufacturers in this group.

The United States began to dominate the propeller driven airliner market a decade after World War I. This domination continued until the end of the piston powered airliner era. These early piston powered airliners are shown by the open, diamond symbols on Figure 2. A light, dashed line is shown on Figure 2 for these piston era airliners. They are approximated by the equation

$$\text{PRODUCTIVITY (ton - knots)} = 0.00015\ (1994\ \text{Dollars})^{1.0} \tag{5}$$

Comparison of Eqs. (4) and (5) shows that the rebirth of propeller driven airliners, powered by turbine engines, has virtually doubled the productivity per "buck" when compared to the piston powered era. A further measure of this rebirth is seen when the Saab 2000 of 1994 is compared to the Lockheed Electra, a turboprop introduced in 1958. The Electra was, after a technical fault was corrected, a superb product for its day. Today, the authors would suggest that advanced rotorcraft such as the tiltrotor strive to achieve at least Saab 2000 productivity per "buck."

These measures of the propeller driven airliner's place in the world of transportation should not go unnoticed by the rotorcraft industry. For example, the Ford Tri – motor 4-AT-B sold for $45,000 in 1926, which escalates to $1.74 million in 1994 dollars. This airliner was an all metal, cantilever wing monoplane; no biplane struts and wire bracing. The three engine configuration provided a usable "one engine out" capability. It offered a 3,960 pound useful load and cruised most economically at 80 to 90 knots at 5,000 foot altitude. The Ford 4-AT-B had a productivity per 1994 "buck" of 94 ton – knots per $1M. Its operating costs were sky high however. By 1936, the Douglas DC-3 had reduced operating costs to 1/2 of the Ford 4-AT-B and commercial aviation was in business to stay, which illustrates the primary importance of total operating costs. This benchmark, twin engine airliner has been hard to beat ever since. In three abreast 18 inch aisle configuration, 21 passengers enjoyed first class accommodations. The DC-3C version sold for $115,000 in 1939, which escalates to $5.67 million in 1994 dollars. The DC-3C's typical useful load was 6,900 pounds. It cruised at 150 knots at 6,000 feet using 550 horsepower from each Pratt & Whitney R-1830-92 piston engine (1,200 hp for takeoff). Its one engine out service ceiling of 9,500 feet at 22,500 pound enroute weight was legendary. DC-3C's had a productivity per "buck" of 90 ton – knots per $1M.

In 1994, airlines started buying Sweden's Saab Model 2000. This twin turboprop transports 50 passengers at 370 knots at 25,000 feet. With 20,500 pound useful load, the Saab 2000 offers about 3,800 ton – knots of productivity for around $14 million in 1994 dollars which gives a productivity per "buck" of 270 ton – knots per $1M. In short, the maturing of propeller driven airliners, unlike rotorcraft, has introduced size and features while improving productivity per "buck." Simple math shows that for modern propeller driven airliners:

$$\begin{aligned}\frac{\text{Productivity}}{1994\ \text{Dollar}} &= \frac{0.00025(1994\ \text{Dollar})^{1.0}}{1994\ \text{Dollar}} = 0.00025\ \text{ton} - \text{knots per dollar} \\ &= 250\ \text{ton} - \text{kts per } \$1\text{M}\end{aligned} \tag{6}$$

The preceding background can be summed up with one very informative graph. Figure 3 shows that equipped twin turbine helicopters, equipped 2 and 4 propeller driven turboprop airliners and equipped turbojet/fan airliners have divided aviation transportation into three speed regions. This in itself is not particularly new information. What is quite significant is that each aircraft class appears able to offer at least one – half (1/2) ton of useful load per $1 million in 1994 dollars. It also appears that few manufacturers have been able to offer equipped, *multi – turbine engine* aircraft at more than one (1) ton of useful load per $1 million.

Figure 3 also includes long dashed curved lines of constant productivity per "buck" expressed in ton – knots per $1,000,000. The lowest level of 100 ton – knots per $1 M passes above most helicopter points and is representative of the 1926 Ford Tri – motor and the 1939 DC-3C. A hint as to where the tiltrotor is starting from and where it might go is suggested by the box and dark arrow on Figure 3. The productivity per "buck" may appear on the low side for the introductory tiltrotor configurations. However, early turboprop and turbojet (i.e., the de Havilland Comet IA) aircraft were improved by 50 to 100 percent in less than a decade. It seems reasonable, therefore, to expect the rotorcraft industry to parallel fixed wing achievements.

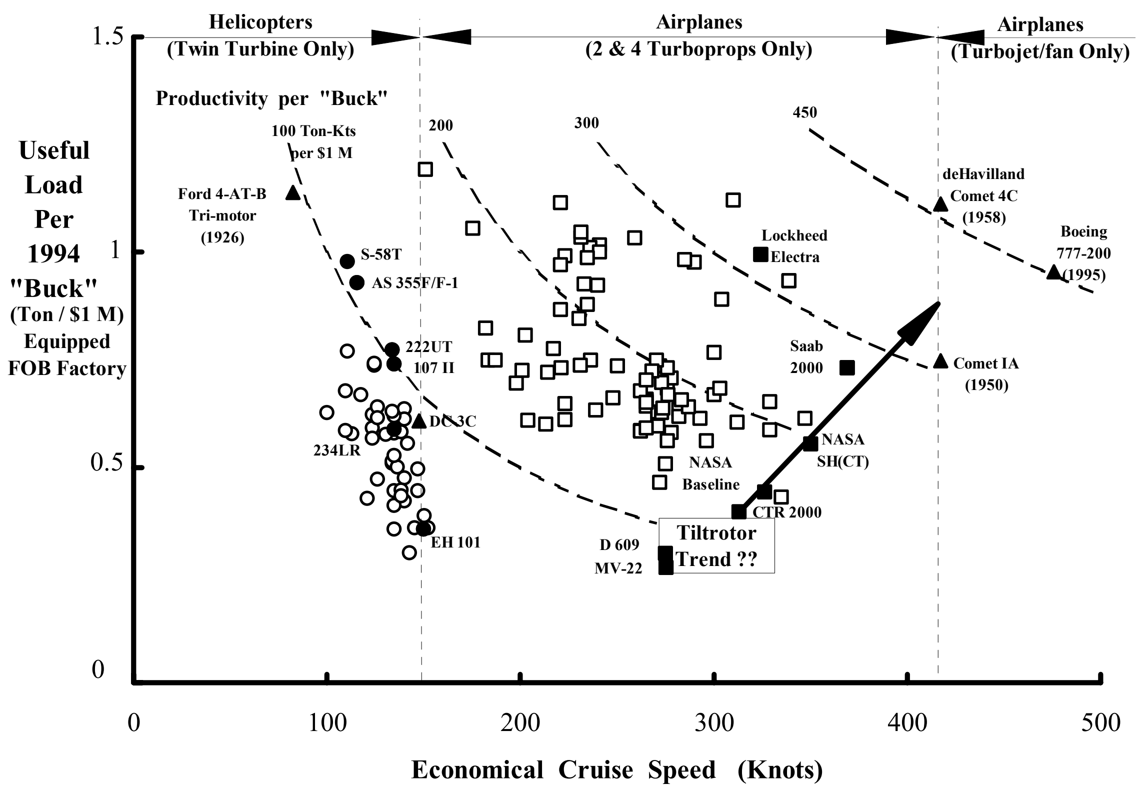

Fig. 3. Helicopter useful load per "buck" *is* competitive but helicopter cruise speed is not.

Helicopter Base Price Estimating

There is a tendency to price aircraft at so much a pound. A frequently quoted number is $1,000 a pound. By not referencing a financial year or whether the pound is takeoff gross weight or empty weight, the estimator is on relatively safe ground. Occasionally an estimate for helicopters will be made by taking the engine(s) price and simply multiplying by four. However, modern electronics can easily be priced at $10,000 a pound. Computer software has added an element, as Augustine set forth with Law Number XVII in Ref. 4, that “weighs nothing, yet is very costly.” Figure 4 shows that helicopter base price bears a scattered relation to weight empty.

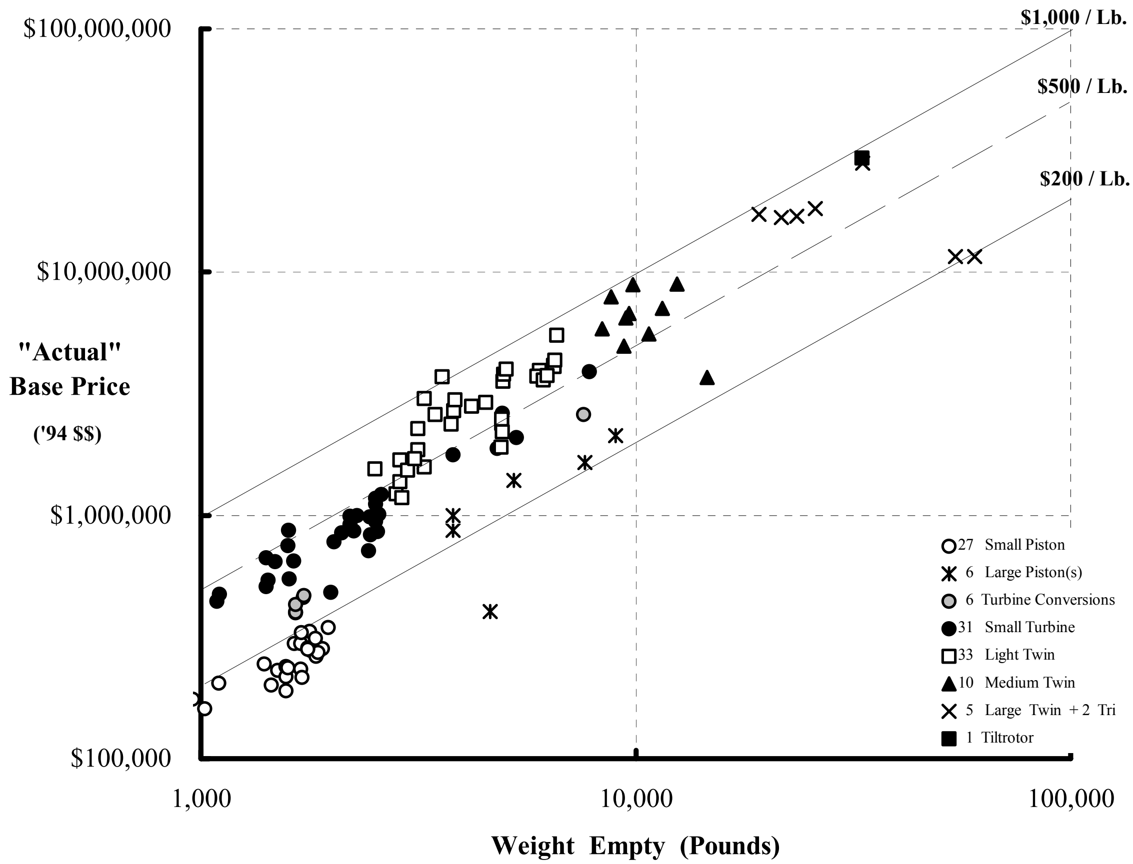

Fig. 4. Estimating purchase price using dollars per pound is not very useful for helicopters.

There are more accurate price estimating relationships that include other major design parameters in addition to weight. A recent example was provided by Ref. 9 in which the *equipped* purchase price of over 100 helicopters was studied using statistical, linear regression analysis. Analysis of *base* purchase price, inclusion of a few more helicopters and other refinements to the Ref. 9 analysis were reported in Ref. 8 along with complete data tabulations. The author’s studies conclude that *helicopter base purchase price in 1994 dollars* can be estimated empirically by Equations (7) and (8) as

$$\text{Base Price} = \$269\,(H)\,(\text{Wgt. Empty})^{0.4638}\,[\text{Total Eng (s). Rated HP}]^{0.5945}\,(\text{Blades Per Rotor})^{0.1643} \qquad (7)$$

where H is the product of five factors and computed by:

$$H = \text{Engine Type} \times \text{Engine No.} \times \text{Country} \times \text{Rotors} \times \text{Landing Gear} \qquad (8)$$

The factors used in computing H are:

Engine Type		**Engine Number**		**Country**	
Piston	1.000	Single	1.000	U. S. Commercial	1.000
Piston (Geared Supercharged)	1.398	Multi	1.344	Russia	0.362
Piston (Converted to Turbine)	1.202			France/Germany	0.891
Gas Turbine	1.794			Italy	1.056

		U. S. Military	0.883
No. of Main Rotors		**Landing Gear**	
Single	1.000	Fixed	1.000
Twin	1.031	Retractable	1.115

The predictive accuracy of Eqs. (7) and (8) is shown by Figure 5. If the relationship were 100 percent accurate, every symbol on this figure would fall precisely on the diagonal line. Many data symbols nearly touch the diagonal line indicating this estimating relationship has very high assurance that it can at least come within 20 percent of the "actual" price 106 out of 121 times or about 88 percent of the time. Quotations are used around the "actual" base price axis of Figures 4 and 5 for two reasons. First, purchase price (whether base or equipped) frequently was negotiable in the year the helicopter was bought. Secondly, we assumed the same inflation regardless of country, manufacturer or helicopter model. Figure 1 showed this inflation trend.

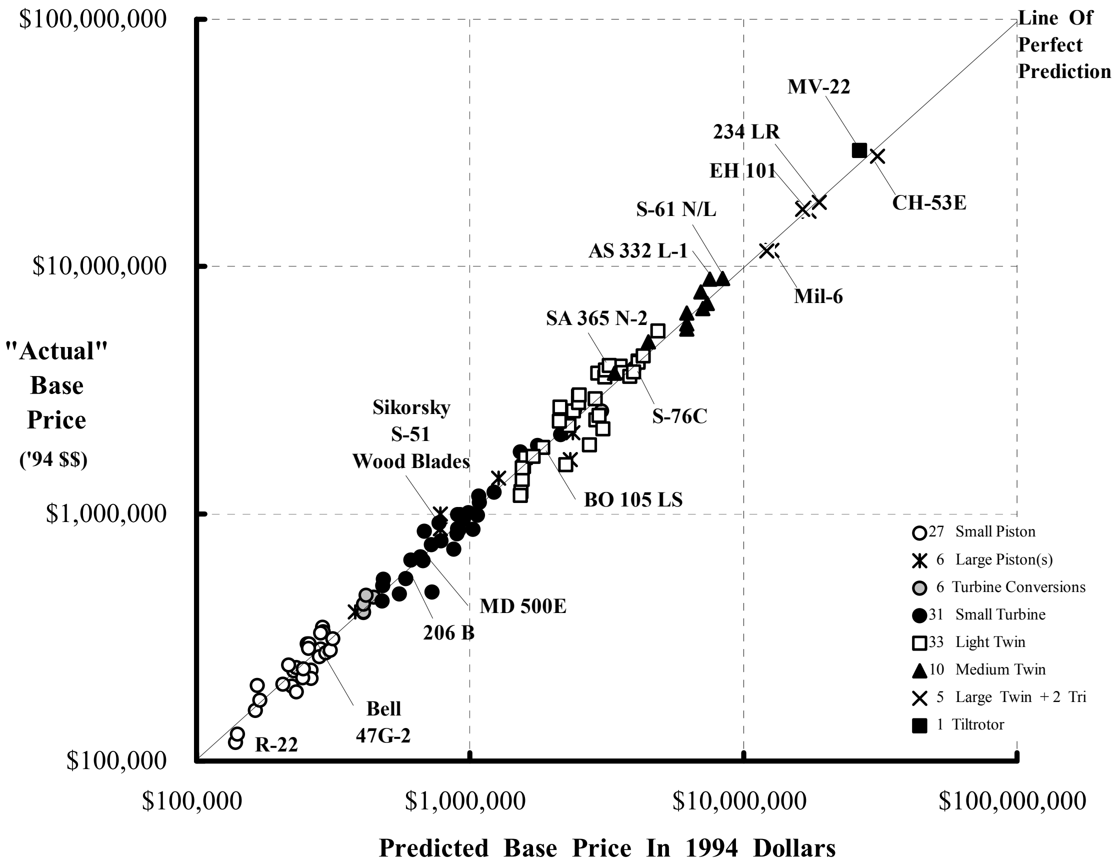

Fig. 5. Out of 120 helicopters and 1 tiltrotor, 106 are price predicted to within ± 20 percent.

The price estimating relationships (i.e., price predicting equations) offered above and later in this paper were developed using linear regression analysis. The analysis sought the minimum error given an array of aircraft business and technical characteristics. This approach is quite similar to that used by weight engineers in their prediction methodology. The approach assumes that it is the product of influential parameters each raised to some exponent – not some weighted sum – that governs the fundamental behavior. During the analysis conducted by the authors, as many as fifteen parameters, including different escalation factors, were statistically involved. Careful sorting of the most promising parameter groups led to the results offered by this paper. The most elusive parameter during this analysis' many trials and errors was the effect of production quantity on purchase price. At no time could parameters associated with a manufacturing "learning curve" be quantified with any statistical assurance. There is, of course, traditional thinking that assumes there is a cost reduction due to learning. However, the authors' present opinion is that rotorcraft *selling prices* are only weakly related (if at all) to production quantity.

Helicopter Base Price Drivers

As shown with Figure 2 and quantified by Equation 3, helicopter productivity per purchasing dollar has, historically, diminished with increasing size and extra features. This trend, while certainly related to time, can be examined using the preceding, statistically based, Equations (7) and (8). This examination is summarized by Figure 6 which shows the base price increase due to six major steps taken as the rotorcraft industry matured the helicopter. Unfortunately, there are only two areas of base price decreases worth noting.

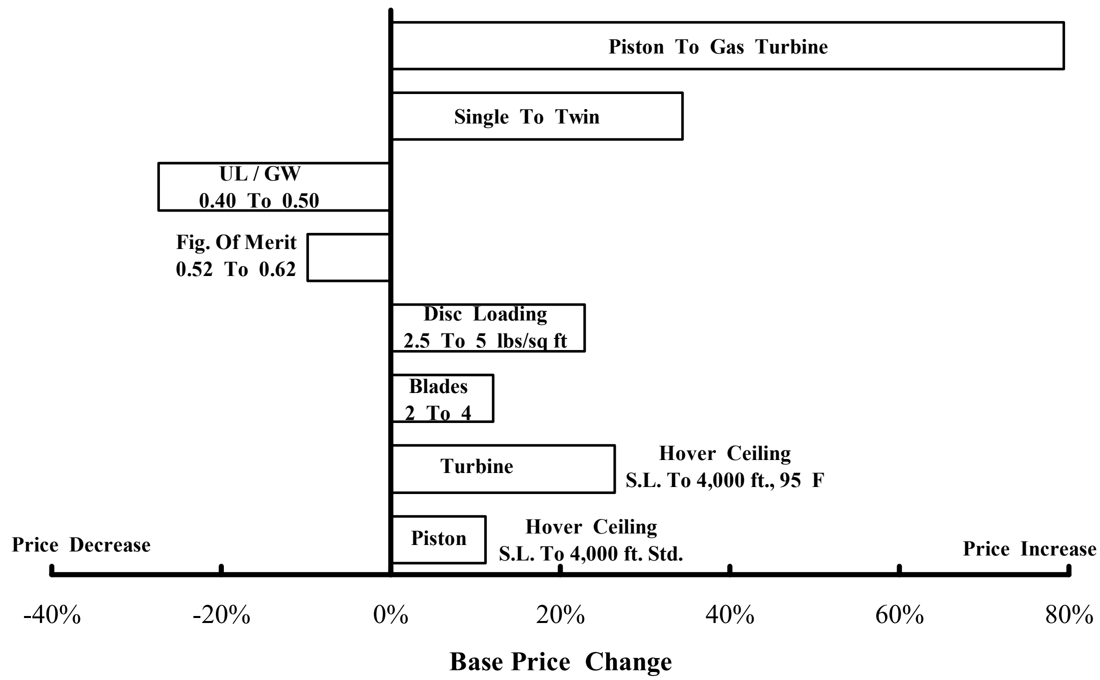

Fig. 6. Most steps in maturing the helicopter have increased price.

A discussion of each configuration step quantified by Figure 6 helps to explain why helicopter productivity per "buck" has such an unsatisfactory historical trend. Consider first, the base price increasing factors quantified by statistical analysis and summarized by Eqs. (7) and (8). The largest single price increasing decision the rotorcraft industry made was to adopt the gas turbine engine. This 79 percent base price increase was initiated in response to U. S. Military requirements in the late 1950s and early 1960s. The objective was to take advantage of the turbine engine's lower weight per horsepower, which increased payload and hence productivity. Today, only the smallest helicopters continue to use the piston engine. Next, consider the 34 percent base price increase associated with the multi – engine configuration step. There have been cases where more than one engine was needed to obtain enough available power given the inventory of available engines. The multi – engine configuration decision has, however, been largely driven by regulatory bodies, engine reliability and industry perceptions related to engine – out safety.

Now consider how technology and design decisions have driven helicopter base purchase price. This requires using Equation (7) plus two additional equations. The first equation leads to an estimate of the total engine(s) rated horsepower parameter used in Equation (7) and is given as

$$\text{Total Eng.(s) HP Req. To Hover} = \frac{\text{Gross Weight}}{550(\text{Aircraft Figure Of Merit})}\sqrt{\frac{\text{Gross Weight}}{2\times\text{Density}\times\text{Rotor Area}}} = \frac{\text{GW}}{550(\text{FM})}\sqrt{\frac{\text{DL}}{2\rho}} \tag{9}$$

The aircraft Figure of Merit (FM) in Equation (9) is a measure of hovering efficiency. A value of FM = 1.0 is ideal. Practical FM values are more on the order of 0.50 to 0.65. The ratio of gross weight to rotor swept area is commonly referred to as disc loading (DL). The density of air (ρ) has a value of 0.002378 slugs per cubic foot at sea level and 59° F. To be useful in the price equations, engine power required at the design altitude and temperature must be corrected to the sea level standard day rating. The horsepower given by Equation (9) *does not* include these corrections. Most engines used in helicopters produce less power at altitude than at sea level, when operated at maximum thermodynamic and mechanical limits. This power loss with altitude is called lapse rate. For non–supercharged piston engines, lapse rate is nearly proportional to the air's density. For gas turbine engines, horsepower variation with altitude depends on both barometric pressure and outside air temperature. Thus, an engine will be rated at sea level so that it produces the required power to hover at altitude with its lapse rate.

The second equation which helps relate technology to base purchase price is really more of a definition. Traditionally, the aircraft industry defines gross weight (GW) as the sum of useful load (UL) and weight empty (WE). One measure of technology progress has been the ratio of useful load to gross weight. Raising this ratio by lowering weight empty at a given gross weight is technical progress. (It may not be, however, economic progress.) Price is influence by weight empty and gross weight (through Equation 9) and productivity is related to useful load. Therefore, rewriting price in terms of useful load and the ratio of useful load to gross weight provides considerable insight. This can be done by noting that

$$\text{WE} = \text{UL}\left(\frac{\text{GW}}{\text{UL}} - 1\right) \quad \text{and} \quad \text{GW} = \text{UL}\left(\frac{\text{GW}}{\text{UL}}\right) \tag{10}$$

The price estimating relationship given by Equation (7) can now be rearranged to uncover several design parameters in ratio form. Skipping the arithmetic steps, the result of substituting Equations (9) and (10) into Equation (7) is

$$\text{Base Price} = \$269(\text{H}) \times (\text{Useful Load})^{1.0583} \times \frac{(\text{Blades Per Rotor})^{0.1643}}{\left(550\sqrt{2}\right)^{0.5945}(\rho)^{0.2973}}\left\{\left[\frac{1}{(\text{UL/GW})} - 1\right]^{0.4638}\left[\frac{1}{(\text{UL/GW})}\right]^{0.5945}\left[\frac{(\text{DL})^{0.2973}}{(\text{FM})^{0.5945}}\right]\right\} \tag{11}$$

This regrouping of configuration parameters in the base price estimating relationship allows quick appreciation of what has happened over the past five decades. Consider first the decision to increase hover ceiling from sea level to something like 4,000 feet. This gave useful operational capability to helicopters. However, larger engines were required because the air density dropped from 0.002378 to 0.002112, a ratio of 0.888. This effect of "thinner" air drove up power required to hover and this drove up base purchase price. The magnitude of this base price increase due to just the increased power required to hover (i.e., before considering engine lapse rate) but with *everything else being equal* is on the order of

$$\text{Price Increase} \approx \frac{1}{(0.888)^{0.2973}} = 1.036 \text{ or about } +3.6\,\% \text{ to raise hover ceiling 4,000 feet}$$

The base price increase must also account for lapse rate. For example, the non–supercharged piston engine, with a lapse rate proportional to air density, makes the price increase for raising hover ceiling 4,000 feet on the order of

$$\text{Price Increase} \approx \frac{1}{(0.888)^{0.2973}(0.888)^{0.5945}} = 1.112 \text{ or } +11.2\,\% \text{ to raise ceiling 4,000 feet}$$

For turbine engines, lapse rate is also significantly affected by temperature. The U. S. Army frequently requires hovering at 4,000 feet with an outside air temperature of 95° F which corresponds to a density ratio of 0.808. Since the typical turbine engine has a 25 percent lapse rate for this design condition, the associated price increase amounts to about

$$\text{Price Increase} \approx \frac{1}{(0.808)^{0.2973}(0.75)^{0.5945}} = 1.264 \text{ or } +26.4\,\% \text{ for 4,000 ft., } 95^{o}\text{F}$$

Price has also increased as blades per rotor have increased. Seemingly endless debate about how blade number affects helicopter vibration and performance can be found in technical reports. Little has been settled on this matter except that, statistically, more blades drive price up. For example, a doubling in blades from 2 to 4 per rotor, *everything else being constant*, increases purchase price by

$$\text{Price Increase} \approx (2)^{0.1643} = 1.121 \text{ or about } +12.1\% \text{ to go from 2 blades to 4}$$

The historical trend of increasing disc loading has raised price even more. Early piston engine helicopters had disc loadings on the order of 2.5 pounds per square foot of rotor area. Modern turbine engine helicopters have disc loadings over 5.0 and, with tiltrotors in the 15 to 20 range, the upward trend continues. This design direction is frequently taken in the belief that size and weight empty should be minimized to minimize price. However, Evan Fradenburgh, in the 1994 Nikolsky Lecture given before the American Helicopter Society (Reference 10), pointed out several fallacies in the high disc loading design approach. Equation (11) quantifies the price penalty of this design approach, the reason being that power has been, historically, more expensive than weight empty in the rotorcraft industry. The base price increase for doubling disc loading, *everything else being constant*, is on the order of

$$\text{Price Increase} \approx (2)^{0.2973} = 1.229 \text{ or about } +22.9\% \text{ to raise disc loading from 2.5 to 5 lbs/ft}^2$$

On the positive side, the industry has invested considerable R & D money on rotor system aerodynamic research (and many details that fall within this general area). This money has been largely spent to raise the helicopter's hovering efficiency (at a given gross weight, rotor area and density). This efficiency is frequently measured by aircraft Figure of Merit (FM). Figure 7 shows representative Figure of Merit values for 52 helicopters as measured in flight test.* An FM increase from 0.525 to 0.625 roughly approximates the payoff of this R & D. The base price

* Discussion of Figure of Merit can be found in most rotorcraft technical books. The ideal Figure of Merit is 1.0. A value of 0.5 says that the rotorcraft will require two times ideal power to hover. The weight coefficient and solidity are defined as

$$\text{Wgt. Coeff.} = \frac{\text{Gross Weight}}{\text{Density} \times \text{Rotor Area} \times (\text{Tip Speed})^2} \qquad \text{Solidity} = \frac{\text{Blade No.} \times \text{Chord}}{\pi \times \text{Radius}}$$

The upper bound line shown on Figure 7 has the behavior of $\text{FM} = \dfrac{1.08}{\dfrac{0.0085 \times \text{Solidity}}{4\sqrt{2} \times (\text{Wgt. Coeff.})^{1.5}} + 1.5}$

reduction created by this 0.10 increment (about a 19 percent improvement) in hovering efficiency, *everything else being constant*, is on the order of

$$\text{Price Reduction} \approx \frac{1}{(1.19)^{05945}} = 0.902 \text{ or about } -9.8\% \text{ for a FM increment of } +0.1$$

The second example of reduced price is improving the ratio of useful load (UL) to gross weight (GW). Figure 8 shows the trend of useful load with gross weight for 121 rotorcraft. The boundaries of the trend represent UL / GW ratios from 0.30 to 0.50. R & D money spent to improve structural efficiency has not always resulted in a greater UL / GW ratio however. This is because otherwise achievable weight empty reductions have often been traded for (1) improved safety (i.e., crashworthy fuel tanks, hydraulic powered controls, IFR instruments and larger passenger doors), (2) improved reliability (i.e., 200 hour Time Between Overhaul increased to 2,000 hours or even "on condition") and (3) reduced maintenance effort (i.e., more access doors). Consider then an increase in useful load to gross weight ratio from 0.40 to 0.50. The base price reduction, *everything else being equal*, is found as

$$\text{Price Indexed (To UL / GW of 0.4)} = \left[\frac{1}{0.40} - 1\right]^{0.4638} \left[\frac{1}{0.40}\right]^{0.5945} = 2.0809$$

$$\text{Price Indexed (To UL / GW of 0.5)} = \left[\frac{1}{0.50} - 1\right]^{0.4638} \left[\frac{1}{0.50}\right]^{0.5945} = 1.5099$$

$$\text{Price Reduction} \approx \frac{1.5099}{2.0809} = 0.726 \text{ or about } -27.4\% \text{ for raising UL / GW from 0.4 to 0.5}$$

Finally, the helicopter's evolution has been paced primarily by military needs. This in itself is a major price driver. "Pure" commercial helicopters have been rare and even these have typically been designed following military standards. The vast majority of commercial helicopters have been derived from components first required and proven by the military. Great strides have been made in improving helicopter safety and reliability. However, the U.S. Army, war aside, typically flies a helicopter less than 150 hours per year, while it is not unusual for commercial operators to exceed 1,500 flight hours per year. Because commercial helicopters are almost always derived from military designs, a 30,000 hour life drive train, which would lower commercial operator costs, has not been developed. It is well to keep in mind, however, that because of military requirements, autogyros gave way to helicopters. Then, with an enthusiastic and growing rotorcraft industry, helicopters reached the commercial world in large and productive numbers.

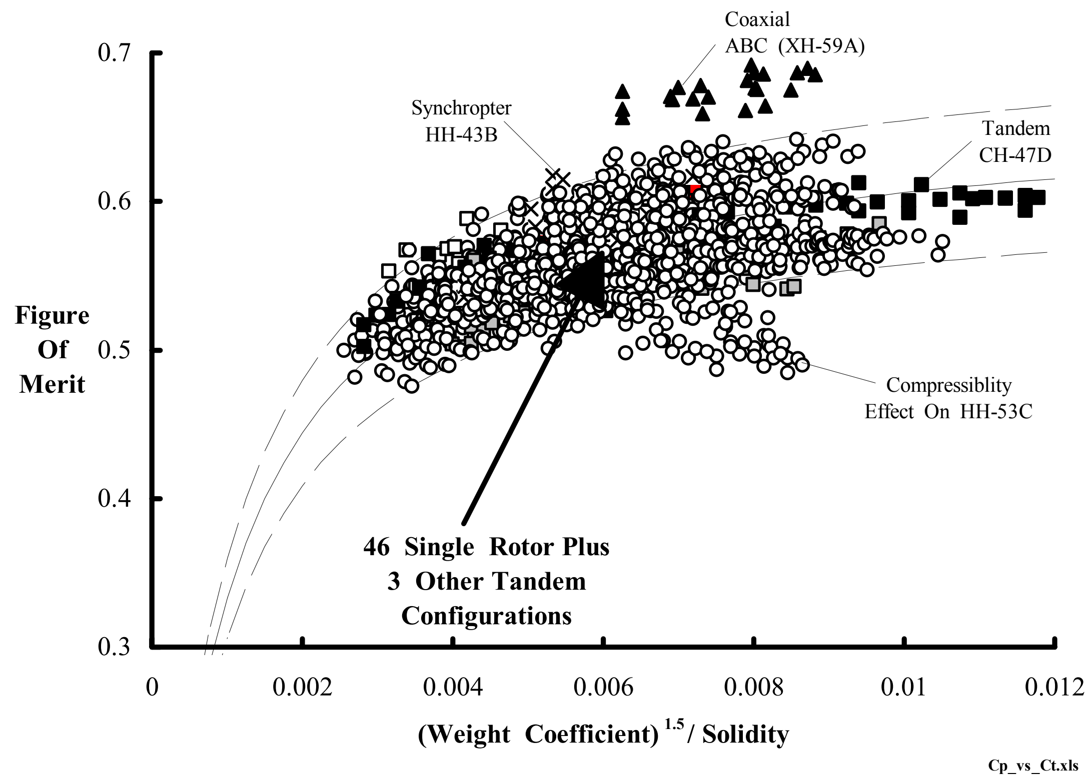

Fig. 7. The industry has significantly increased hovering efficiency over five decades. (The primary data sources are U. S. Army Aviation flight test reports.)

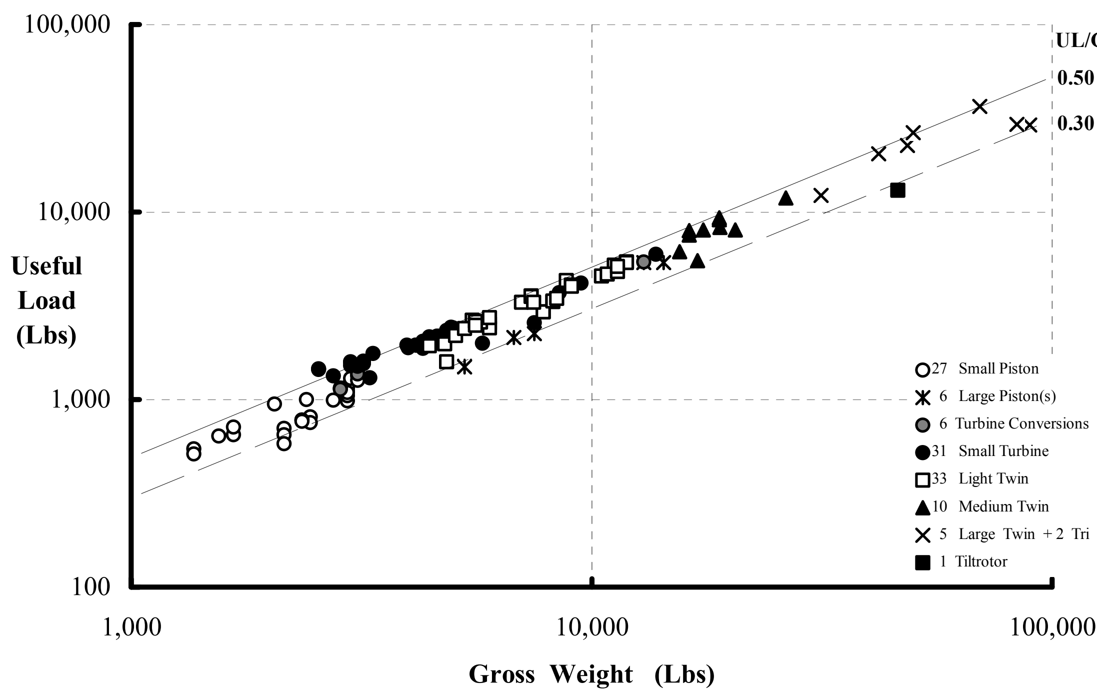

Fig. 8. The ratio of useful load to gross weight depends on the balance between added features and otherwise achievable structural weight reduction.

Helicopters Versus Propeller Driven Airplanes

The rotorcraft industry has long had the objective to expand its position in the world of transportation as Reference 11, for example, records. In this regard, the airplane has been the aircraft against which the helicopter must compete. Therefore, understanding the helicopter's competitor and its pricing trend can be very helpful in reaching this expanded market objective. The airplane side of the business has introduced improvements paralleling the helicopter and, by large cruise speed gains, maintained a favorable productivity per "buck" as Figure 2 showed. Helicopters, on the other hand, appear to have carved out a VTOL niche that closely parallels progress made in General Aviation. Few helicopters have been developed for commuter airline service.

The commercial airplane market is divided into two broad segments. The first segment offers General Aviation (GA) products while the second segment sells airliners. Both propeller driven and jet driven aircraft are available within each segment. Helicopters currently appear to compete primarily with the General Aviation propeller driven airplanes as will be seen shortly. One or two large helicopters may compete with turboprop commuter airliners. However, it is more likely that advanced rotorcraft, such as the tiltrotor, will offer real competition in the airliner market segment as Figure 3 suggested.

To examine helicopters versus propeller driven airplanes, a survey of 126 GA and 163 airliners was made. This airplane data bank, similar to that prepared for helicopters, showed first that inflation has been different for each of the three aircraft classes. A comparison of escalation factors to inflate then year price to 1994 dollars is shown by Figure 9. (A complete tabulation of Figure 9 data is provided in the appendices of Reference 8.)

The difference between equipped and base price was a major variable in the helicopter, General Aviation, airliner data bank. This difference was most significant for General Aviation and of lessor importance for helicopters. For airliners, the quoted prices did not distinguish

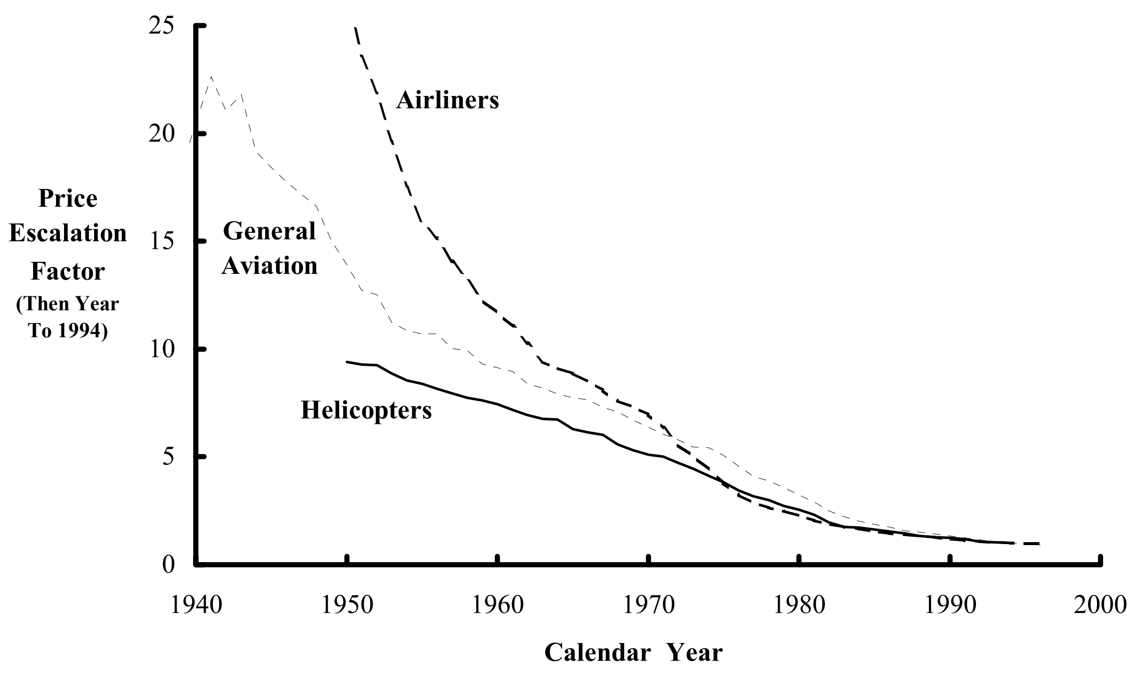

Fig. 9. Price escalation in the aircraft industry varies considerably between products.

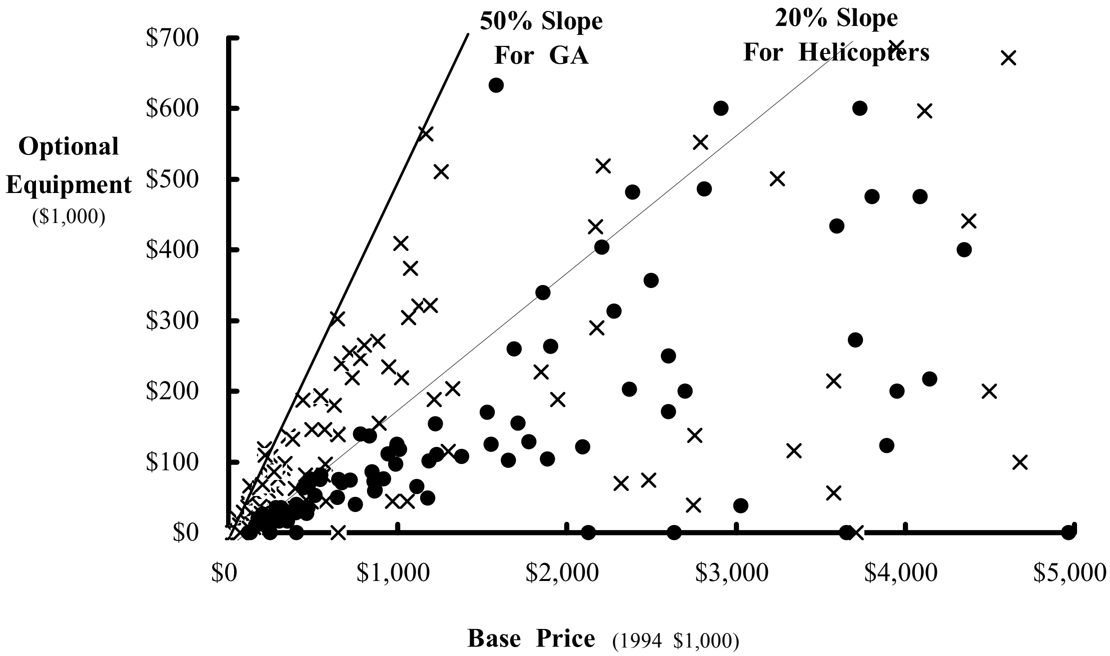

Fig. 10. Optional equipment pricing differs significantly for helicopter and General Aviation market segments. (Symbols are • for helicopters, × for GA).

between equipped and base prices. Presumably, satisfying air regulations virtually defines needed safety and avionics equipment so that base price equals equipped price for the airliner class. The difference between equipped and base price is compared for helicopters and GA airplanes in Figure 10. For General Aviation aircraft, optional equipment can increase base price by as much as 50 percent. Helicopter marketing appears to reduce the optional equipment choices so that no more than a 20 percent increase over base price is likely. On average, helicopter optional equipment increases base price by 10 percent while for GA aircraft the average increase over base price amounts to 21 percent. Apparently, optional equipment, whether for GA or helicopter aircraft, plateaus at about $600,000 to $700,000.

No attempt was made in this survey to investigate and compare the actual optional equipment lists offered by either aircraft class. Therefore, it is possible that some of the price difference between helicopters and airplanes shown on Figure 2 is due to optional equipment.

The relationship of General Aviation and airliner base prices to weight empty, shown in Figure 11, indicates the distinct difference in these aircraft classes. Regression analysis shows that the base price of General Aviation aircraft can be approximated to the first order as

$$\text{General Aviation Base Price} = \$0.0706\,(\text{Weight Empty})^{1.9742} \qquad (12)$$

Apparently GA base price increases nearly in proportion to the square of weight empty. In sharp contrast, airliner base (i. e., equipped) price increases nearly linearly with weight empty behaving approximately as

$$\text{Airliner Base Price} = \$159\,(\text{Weight Empty})^{1.0902} \qquad (13)$$

Neither approximation is very accurate despite the appearance given by Figure 11 with its log – log scale. The GA base price relationship of Eq. (12) has a statistical accuracy of $R^2 = 0.9821$, which translates to 105 out of 126 aircraft predicted to within 20 percent. The airliner price relationship given by Equation (13) has much poorer statistical accuracy having $R^2 = 0.9554$. For this airplane class, only 100 out of 163 airliners are predicted to within 20 percent.

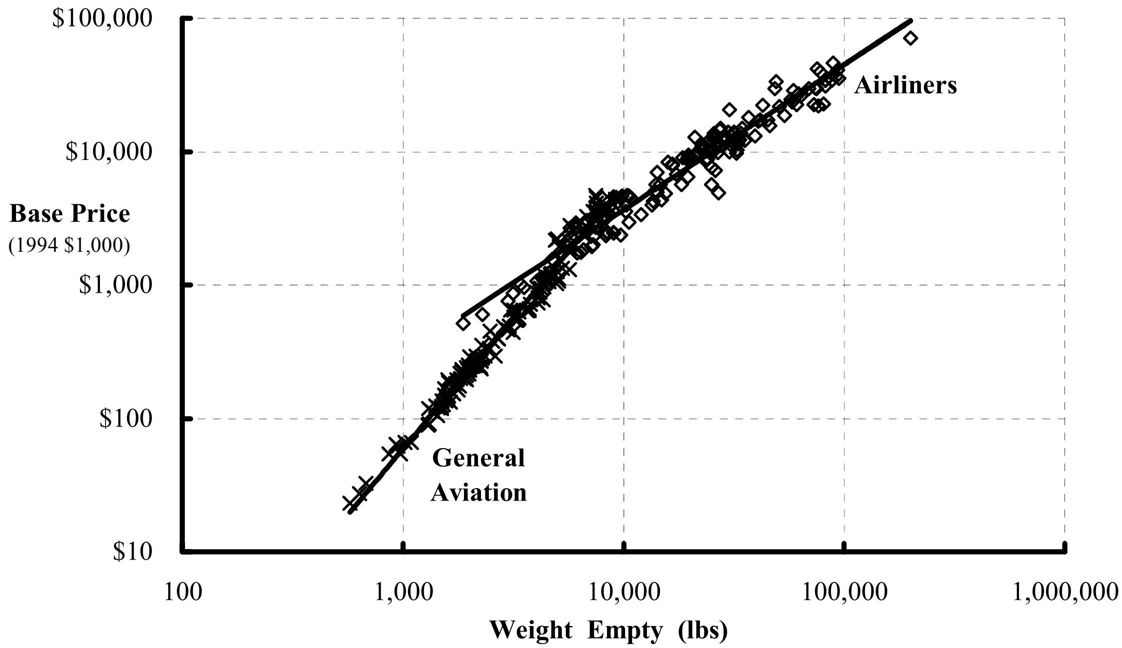

Fig. 11. Airliner and GA airplane prices vary quite differently with weight empty.

All Aircraft Pricing Relationship

Figures 4 and 11 both show the relatively poor correlation of base price with weight empty as the only driving parameter. Therefore, an All Aircraft data bank was formed. The objective was a regression analysis of helicopters, General Aviation and airliners as one group. This combined group was statistically analyzed assuming that all data fit the following equation:

$$\text{Price} = \text{Constant} \times \left(\text{Class} \times \text{Factors}\right) \times \left(\text{Weight Empty}\right)^{N} \times (\text{Total Takeoff Horsepower})^{M}$$

The previous efforts uncovered several parameters associated with the "Factors" constant in this equation for helicopters. Therefore, the task was relatively simple. Three, primary class constants were allowed in the regression analysis to account for helicopter, General Aviation and airliner groups. The airliner class was assigned a value 1.0 and the regression analysis was asked to find relative class factors for the helicopter and GA groups. Subordinate factors in the helicopter group obtained from previous efforts were used as a guide. The authors quickly found that, despite introduction and subsequent removal of an abundance of factors, the weight and power exponents remained close to $N \approx 0.48$ and $M \approx 0.58$.

The correlation of predicted and "actual" price achieved for 409 aircraft is shown by Figure 12. The regression analysis was accurate to $R^2 = 0.9949$ which corresponds to only 34 aircraft not predicted to within 20 percent. Only 5 airliners out of 163, 17 out of 126 GA and 12 out of 118 helicopters lay outside the 20 percent accuracy range. The price referred to is base price for rotorcraft and General Aviation aircraft. Airliners can not, by regulation, be operated commercially without most equipment that is optional for General Aviation. Thus, the base price for airliners includes equipment similar to fully equipped GA. This, of course, biases the general correlation; however, it is doubtful that the airliner base price differs by more than \$700 K from equipped price which is less than a 10 percent biases. This is within the order of accuracy of this All Aircraft study.

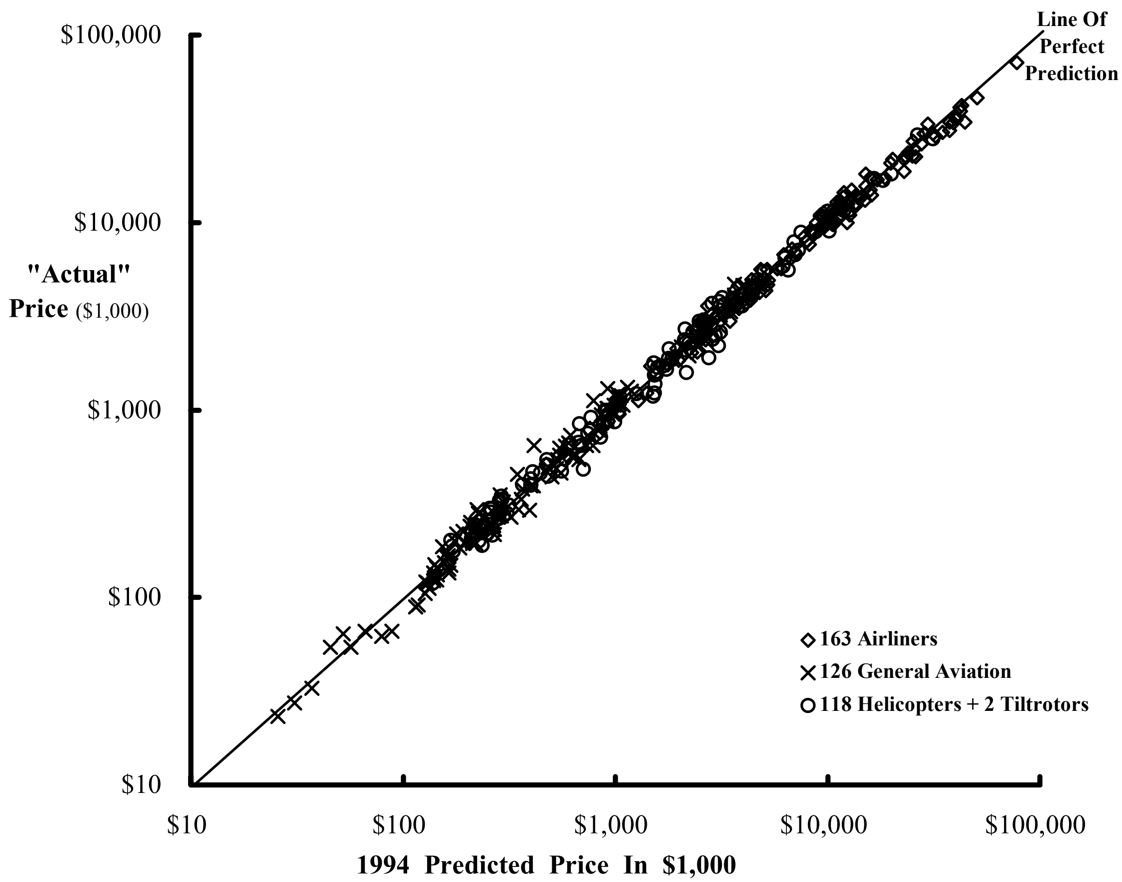

Fig. 12. Out of 409 aircraft, the price of 375 is predicted to within 20 percent.

Each aircraft class had a unique price estimating relationship used to predict price on Figure 12. These price predicting equations, obtained from regression analysis, are:

FOR 118 HELICOPTERS + 2 TILTROTORS

$$\text{Price} = \$236.77\ (H)\ (\text{Blades Per Rotor})^{0.2045}\ (\text{Wgt. Empty})^{0.4854}\ [\text{Eng (s). Rated HP}]^{0.5843} \qquad (14)$$

where H is the product of six factors and computed by:

H = Engine Type × Engine No. × Country × Rotors × Landing Gear × Pressurization

The factors used in computing H are:

Engine Type		Engine Number		Country	
Piston	1.000	Single	1.000	U. S. Commercial	1.000
Piston (Converted to Turbine)	1.180	Multi	1.352	Russia	0.330
Gas Turbine	1.779			France/Germany	0.860
				U. S. Military	0.838

No. of Main Rotors		Landing Gear		Pressurized	
Single	1.000	Fixed	1.000	No	1.0
Twin	1.046	Retractable	1.104	Yes	1.135

FOR 126 GENERAL AVIATION

$$\text{Price} = \$192.38\ (GA)\ (\text{Wgt. Empty})^{0.4854}\ [\text{Eng (s). Rated HP}]^{0.5843} \quad (15)$$

where GA is the product of four factors and computed by:

$$GA = \text{Engine Type} \times \text{Engine No.} \times \text{Trainer} \times \text{Pressurization}$$

The factors used in computing GA are:

Engine Type		Engine Number		Trainer		Pressurized	
Piston	1.000	Single	1.000	No	1.000	No	1.0
Piston (Supercharged)	1.249	Multi	1.352	Yes	0.710	Yes	1.135
Gas Turbine	2.101						

FOR 163 AIRLINERS

$$\text{Price} = \$522.40\ (AP)\ (\text{Wgt. Empty})^{0.4854}\ [\text{Eng (s). Rated HP}]^{0.5843} \quad (16)$$

where AP is the product of three factors and computed by:

$$AP = \text{Plane Type} \times \text{Country} \times \text{Pressurization}$$

The factors used in computing AP are:

Plane Type		Country		Pressurized	
Land Based	1.000	Russia	0.570	No	1.000
Flying Boat	1.790	All Others	1.000	Yes	1.135

The pressurization factor was assumed to also apply to helicopters and advanced rotorcraft. Finally, the authors noted that with 13 parameters or more, Microsoft EXCEL Version 7 refused to perform regression analysis.

Comparisons At Equal Size Factor

The preceding statistical regression analysis suggested a pseudo, universal, all aircraft size factor (i.e., a scaling parameter) could be used to separate features from size as a price driver. Rather than estimating price by weight empty alone, the analysis recommended that total engine(s) rated takeoff horsepower also be included as a fundamental parameter. This Size Factor appears to be

$$\text{Size Factor} = \left(\text{Wt. Empty}\right)^{0.4854}\left[\text{Total Engine(s) Rated HP}\right]^{0.5843} \quad (17)$$

Thus, for constant configuration parameters (i.e., engine number and type, country, pressurization, etc.), price will vary linearly with the size factor given by Equation (17).

This size factor is very helpful in understanding airplane pricing and when comparing rotary wing aircraft to fixed wing competitors. For example, the evolution in fixed wing aircraft from a simple Piper Cub of pre World War II vintage to the most advanced, 1994 turboprop airliner is shown with Figure 13. The interpretation of Figure 13 is summarized with the following points:

1) Two distinct slopes in the data are clearly defined. Airliner prices vary linearly with the Size Factor (i. e., a slope of 1.0). General Aviation prices rise faster with the Size Factor having a slope of 1.6. This difference in slope for GA aircraft comes about primarily because features such as pressurization, engine type changes from single to turbine, progression from single to multi – engine are added with increasing size factor. This is also why the productivity per “buck” appears

adverse, relative to airliners, on Figure 2. Similar changes in engine type and number as size factor increases has adversely affected helicopter productivity per "buck."

2) The airliner trend represents nearly constant configuration. Virtually all models have flaps, constant speed propellers, are multi–engine and are land based with retractable landing gear. It should be noted that the transition from large piston engines to turboprops was made with less than a 10 percent increase in price as Ref. 8 showed. Therefore, no engine type factor was included in Eq. 16. However, this transition to gas turbine engines virtually doubled GA and helicopter prices as Eqs. 15 and 14 disclose. The authors are unable to explain this large difference in the engine type factor between airliners and GA or helicopters. It should be noted that helicopter conversion from piston to gas turbine is priced much lower as Eq. 14 notes.

3) The very smallest end of General Aviation is represented by the well known Piper Cub, Model J-3. The slope is 1.0 because these three models were only improved by installed power increases, small weight empty growth and with no features added.

4) The progression from Piper Cub, with minimum features, to airliners with fully developed technology incorporated, raised prices by a factor on the order of 4.5. This is suggested by the light, dashed line extrapolated to larger size from the Piper Cub.

5) Finally, be aware that no Russian or flying boats are included on Figure 13. Data for these airplanes is provided in Reference 8.

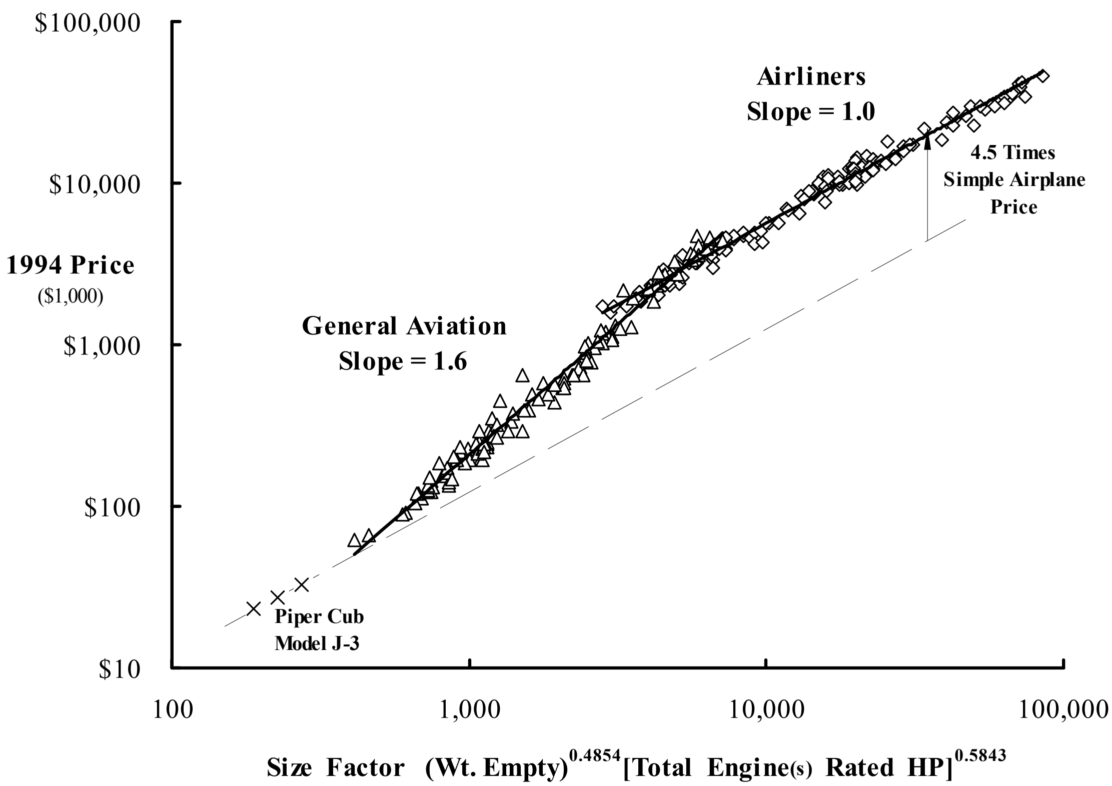

Fig. 13. Price varies linearly with size factor provided other configuration parameters (i.e., engine type and number, country, etc.) remain constant.

Helicopter data points, when added to Figure 13, show that this type of rotorcraft approximately parallels fixed wing historical trends. This comparison is illustrated with Figure 14. (Fixed wing data points have been removed for clarity.) While there is more "scatter" in the helicopter points because of the price of features and blade number, helicopters parallel fixed wing but at roughly a 50 percent premium in price. It appears, based on Figure 14, that the vast majority of helicopters have found a VTOL niche in the General Aviation marketplace despite the 50 percent price premium for VTOL. The authors, in Reference 8, attempted to explain and justify this premium with a price comparison between the Boeing 234 LR and the de Havilland Dash 8-300A. These two aircraft were chosen as representative commuter airliners of comparable weight empty and vintage. The authors were unable to fully explain the 50 percent price premium shown by Figure 14. This price premium for VTOL plus the low cruise speed associated with edgewise flying rotors accounts in large measure for the helicopter's comparatively low productivity per "buck" shown by Figure 2.

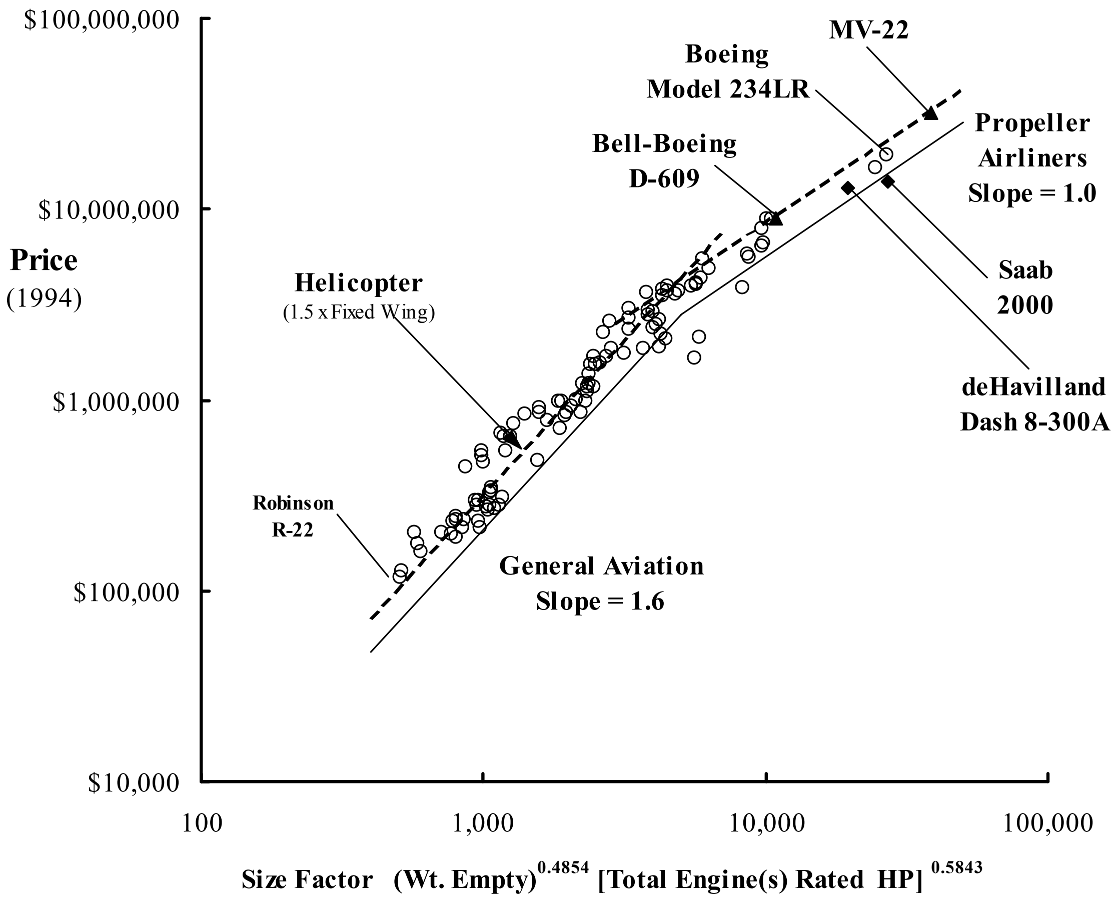

Fig. 14. Helicopter prices appear to parallel General Aviation and Airliner historical trends, but at roughly 50 % higher price.

Finally, the MV-22 and the recently announced Bell – Boeing D-609 tiltrotor aircraft appear to offer a fair speed return on installed power as Figure 3 suggests. This is a breakthrough for the rotorcraft industry. However, the MV-22 estimated price is about $30 million and the D-609, still in the preliminary design phase, has a rumored price close to $9 million. Figure 14 shows that, compared to modern turboprop airliners such as the Saab 2000, the price of this new VTOL rotorcraft must be reduced if the industry intends to expand into the commuter airliner marketplace. In short, the price premium for VTOL is too high.

Conclusions

1. Designing commercial aircraft for minimum weight DOES NOT result in minimum price.

2. Helicopter productivity per "buck" goes down as size goes up and features are added. This is a General Aviation trend. It is not an airliner trend. This rotorcraft problem is caused by :
    a. excessive power loading due to a high disc loading, minimum weight empty design approach, and
    b. poor speed return from the power loading investment.
3. At equal size factor, defined as $[\text{Wgt. Empty}]^{0.48}[\text{Total Engine(s) Rated HP}]^{0.58}$, it is very hard to explain a 30 % to 50 % price difference between rotary and fixed wing aircraft.
4. The rotorcraft industry has overcome the helicopter's low cruise speed with the tiltrotor. Now the industry must reduce the price premium for Vertical Takeoff and Landing.

Acknowledgments

Mr. Evan Fradenburgh was privileged to give the 14th Nikolsky Lecture at the May 1994 AHS Forum. He spoke about the high costs of rotorcraft. His "call to arms" to the technical members was not only timely but very motivating. We thank him for encouraging the application of technical expertise to the rotorcraft industry's business and financial situation.

Mr. Henry Lee, a member of the Advanced Design Team in the Aeroflightdynamics Directorate, prepared the General Aviation data base included here. It is from this data bank the authors expanded and revised previous views about helicopter price trends. Henry's detective work in uncovering raw price and configuration data was immensely valuable to the overall study. We thank him very much.

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