Factors Affecting the Cost of Airplanes

Presented at the Aircraft Operations Session, Fourth Annual Meeting, I. Ae. S.

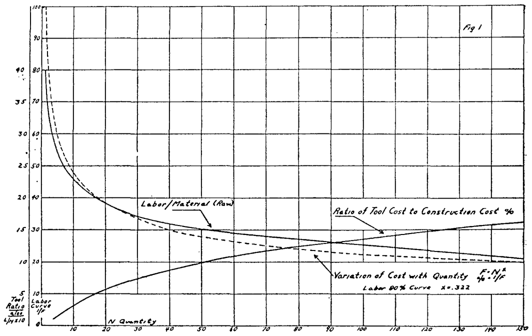
T. P. WRIGHT, *Curtiss-Wright Corporation*

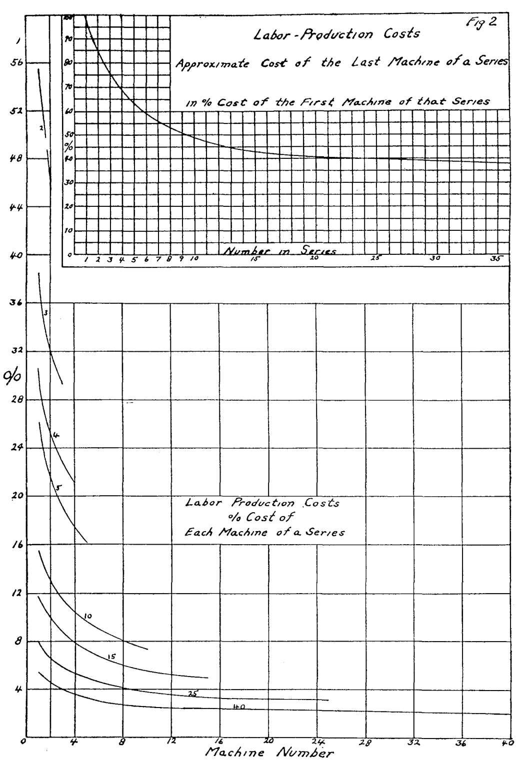
INTRODUCTION

THIS subject is one which can always be relied upon to start a discussion whenever it is raised in aircraft circles. Great differences of opinion will be voiced as to the relative importance of various factors, depending somewhat on whether the discussion is between persons in the industry who are engaged in sales, engineering, design or factory work. The attitude of those outside the industry is usually quite supercilious with the intimation present that everyone engaged in the design, development, or construction of airplanes is a sort of prima donna. Therefore, because of the rather hazy information which seems to surround the subject, it appears in order to discuss the problems from several points of view in an effort to arrive at logical conclusions.

The effect of quantity production on cost, particularly, requires study as in this respect more than in others, there exists a lack of appreciation of the variation which occurs. Recently the matter became of increasing interest and importance because of the program sponsored by the Bureau of Air Commerce for the development of a small two-place airplane which, it was hoped, could be marketed at $700 assuming a quantity of ten thousand units could be released for construction.

The present writer started his studies of the variation of cost with quantity in 1922. A curve depicting such variation was worked up empirically from the two or three points which previous production experience of the same model in differing quantities made possible. Through the succeeding years, this original curve, which at first showed the variation in labor only, was used for estimating purposes and was corrected as more data became available. The form which this curve takes when plotted on plain cross-section paper is shown in Fig. 1. On this figure there is also shown the variation of the ratio of labor to raw material as quantity varies. The correcting of curves of this type by new points of actual experience resulted in data which permitted other curves to be plotted, showing the variation of raw material, purchased material, and finally, of the whole airplane, against quantity.





Effort was also made to plot the cost of each machine of a series in percent of the total cost of the series for varying quantities. The work along this line is shown in Fig. 2 which, however, must be considered as more approximate in accuracy than the others because of the greater difficulty in securing reliable empirical information on the relative cost of each machine of a series, since accounting methods seldom reveal such data. However, the curves of Fig. 2 are believed to show the general shape of curves and trend of data of this kind.

Design Factors

Type of construction is obviously one factor which governs cost. Design not only affects relative cost in a given quantity but also may affect the shape of the curve which shows the variation of cost with quantity.

In the early days, the so-called stick-and-wire-and-fabric construction maintained, using wooden members for beams and struts with metal fittings at the joints and wires as truss members. This type of construction was eminently suited to quickly and cheaply constructing a prototype machine. It also proved economical in quantities which have maintained for airplane construction up to the present time. In spite of the inherent cheapness which this type of construction permits in small quantities, it is somewhat doubtful as to whether or not so steep a curve of cost reduction for increasing quantity would maintain for this type when compared with others.

Next there was a prevalence of the use of welded steel tubing in lieu of the stick-and-wire construction, almost exclusively in the fuselage and extensively, but somewhat less, in the tail surfaces and wings. Fabric was still used as a covering and wooden beams were the rule. This type of construction permitted the use of jigs and fixtures which, when any reasonable quantity was involved, allowed quite cheap construction. The operation of welding, however, was one which in large quantities could not progress in time saving beyond a certain point. The chief gain, therefore, in reducing production costs was in the use of better tools and fixtures rather than anything inherent in the construction which lent itself to progressively cheaper fabrication in large quantities.

Finally, we have come to the general use of monocoque construction wherein sheets of relatively thin material are formed and attached together by rivets. This is a type of construction which to an even greater extent requires the use of proper tools and fixtures for cheap quantity production and, partly for this reason, is relatively expensive in prototype or small quantities. For constructing a prototype airplane it is estimated that the use of monocoque construction increases its cost, when compared to the older types, by from fifty to one hundred percent. This same ratio holds in small quantities but in larger quantities greatly decreases and in very large quantities would, it is believed, indicate the reverse in tendency as to labor costs.

The cost of raw materials used in monocoque construction is only slightly more than in the older types. For an all-metal plane of alclad, it appears that an average price of sixty cents per pound of material purchased will hold for the sheet metal used and about one dollar per pound for the sum total of castings, rivets, extruded sections, etc. For all the metal used, a price averaging about seventy-one cents per pound of material purchased is about what will maintain. When considering the whole structure of the airplane, this figure increases to about one dollar a pound, as other parts, such as wheels, oleo struts, and purchased items on which labor is expended by some vendor will average higher than raw metal. This figure, in turn, must be increased for factor of waste when determining the price per pound of "finished product" instead of "material purchased," arriving at a figure of about one dollar and a quarter per pound for the whole airplane and ninety cents per pound for metal only (assuming a quantity of about twenty-five units).

Now let us compare material costs of all-metal construction to material costs of tube, fabric and wood construction. As a guide it should be noted that airplane spruce is by no means cheap and has a high waste percentage. Cost of dope, paint and fabric is also relatively high. Assuming, therefore, that the cost of materials is only slightly more (if any) for all-metal construction than for the older types (and actual records bear this out), it is important to note that in very large quantities the prospect of obtaining the hoped for cheap monocoque construction is satisfactory from this standpoint because of the relatively greater importance of material as compared to labor as quantities increase. This will be more clearly seen by referring to the labor/material curve in Fig. 1 where the ratio is reduced from about four to one in a quantity of one ship to about one to one in a quantity of one hundred and fifty ships.

Labor involved is, for the most part, a matter of joining. As mentioned before, welding is not particularly economical from this standpoint and particularly is not susceptible of great time savings in mass production. Riveting is also extremely expensive at the present time but is sufficiently better adapted to tooling and further developments in automatic riveting machines so that for large quantities in the future it holds good prospects of being accomplished economically. Spotwelding has a great deal of merit as a cheap method of joining parts and the rapid strides now being made in the development of electric spotwelding equipment for use in joining aluminum alloy parts is encouraging. The use of stainless steel (spot welded) possesses the same promise from the cost standpoint although its general adaptation from the standpoint of design efficiency is still open to question, except perhaps for limited application.

It therefore appears that the present trend towards the use of monocoque construction for all parts of the airplane is efficient from the structural, weight and aerodynamic considerations and may also be expected to show good results from the cost standpoint when construction is undertaken in really large quantities.

Naturally, such generalities as simplicity of design, reduction of parts, design of simple parts, and use of forgings must, as design factors, be applied to any type of construction in order to attain economy. In addition to the trend in material costs and riveting time reductions applied to monocoque construction, the possibilities of stamping large contours in various types of dies fitted to large presses represents a means of labor saving for this type of construction.

Tooling

In Fig. 1 a curve is shown which indicates the trend of relative tool costs plotted against production quantity. The tooling factor and the susceptibility of a given type of construction to the use of tools is important in deriving the slope of the production curve. Many of the factors of the different types of construction discussed have been mentioned in connection with their susceptibility of tools application.

From the design standpoint, sight has frequently been lost of the need for considering future tooling at the time parts are drawn. This particularly applies in the case of forgings where, when production orders are received, it is frequently necessary to re-design large numbers of parts in order to substitute forgings for built-up construction. Analysis has shown that contrary to popular belief, the quantity of parts necessary to make a forging die pay is quite small. It is usually possible, in an order of twenty-five ships to use forgings for a great many parts and if the quantity is one hundred ships, there are very few small parts which cannot economically be so made. In Fig. 5 there is shown a photograph of a number of forgings used on a plane manufactured in a quantity of fifty units. In every case, an analysis was made of the exact saving involved before the forging was decided upon. The results were extremely gratifying.

Changes

The tremendous cost of changes introduced into a production order during construction is too well known to require emphasis. This cost is involved, not only in shop delays but in the engineering expense of re-designing. It is appreciated that in a rapidly moving art such as aviation, changes are more or less inherent. However, as standardization of type construction becomes more general, it may be expected that less changes will be required during production runs in the future. In using the curve developed in this paper, it should be recognized that the factors derived are based on the assumption that no major changes will be introduced during construction.

Effect of Size

The factors which apply when considering the effect on cost of size and which favor decreased cost with increased size are the following:

First, the number of parts does not increase proportionately to size increase. Next, in a large airplane, there are less parts of minimum size and gauge, thus favoring ease of handling to some extent. Next, within certain limits, there may be expected to maintain a slightly smaller unit weight as size increases. It is appreciated that the so-called square-cube rule will enter in at some stage, invalidating the above statement. However, the effect of this rule is counterbalanced by the structural inefficiency of minimum gauges used in small airplanes and of the greater spread in large airplanes per unit of structural weight for such items as crew, radio, instruments, etc. Also, there should be mentioned the fact that there is better access to parts in large machines than maintains in the cramped quarters of small ones.

On the other hand, there is the greater handling labor of very large units in assembly which is decidedly more than in small machines.

All in all, it is believed that when measured in dollars per pound of structural weight there will be a decreasing cost for machines up to about twenty-five thousand pounds with a very gradual increase above that figure.

Effect of Quantity

The factors which make possible cost reductions with increase in the quantity produced are as follows:

Labor

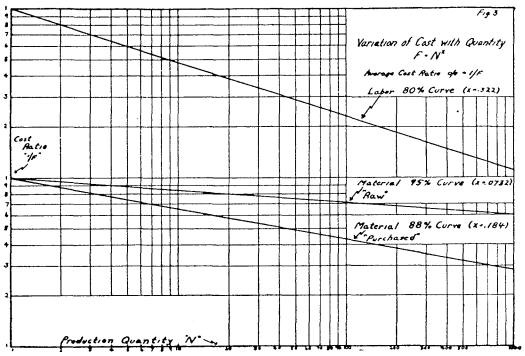
The improvement in proficiency of a workman with practice and particularly if time studies for economy of motions are made, is well known. This applies particularly in assembly operations but also holds for other types of work. It may also be anticipated that there will be less changes to disconcert the workman as the quantity increases. Another factor is the greater spread of machine and fixture set up time in large quantity production. As previously mentioned, one of the principal factors is the economy of labor which greater tooling can give as the quantity increases. A final factor allied to the one last mentioned, is the ability to use less skilled labor as more and more tooling and standardization of procedure is introduced.

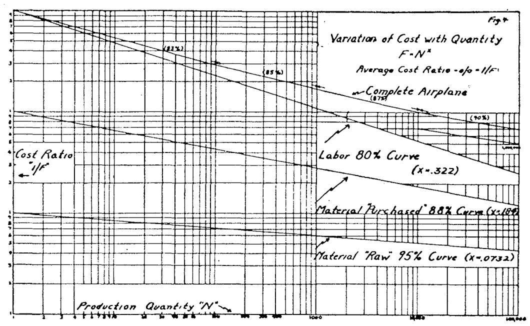
In developing the curve which shows variation of labor cost with production quantity, it became evident that its form was of the type depicted by the formula $F = N^X$. This resolves into an expression for X as follows:

$$X = \frac{\operatorname{Log} F}{\operatorname{Log} N}$$

Where F = a factor of cost variation proportional to the quantity N. The reciprocal of F then represents a direct percent variation of cost vs. quantity.

A curve may be plotted which shows directly the relationship between the two variables and when plotted on log-log paper, it becomes a straight line. In Fig. 3 such a curve appears; there called the eighty percent curve which is represented by a value of .322 for the exponent X in the above formula. This "eighty percent" has a definite meaning in that it represents the factor by which the average labor cost in any quantity





shall be multiplied in order to determine the average labor cost for a quantity of twice that number of airplanes. On Fig. 3 the curves are so plotted as to be susceptible of use for quantities which are likely to maintain for some time to come. On Fig. 4 the paper is arranged to carry the numbers in production to very large amounts, of particular interest in noting the possible future of airplane costs and of use in making certain comparisons mentioned further along.

Material

Material also decreases in cost as quantity increases due to the following reasons:

First, the amount of waste is cut down. When comparing the light weight of the structure of the airplane with the actual weight of material purchased in order to construct it, it has been found that in a quantity of one to five units this waste is as large as forty percent. It reduces rapidly as quantity increases, to twenty-five or thirty percent in quantities of twenty-five to fifty units and down to twenty percent in a quantity of one hundred units. Greater cutting efficiency and more economical purchasing from the standpoint of matching parts from sheets of a given size partially explain this reduction. Then too there is also a reduction in material cost with quantity due to the reflected effect of the reduction of labor which at various stages has been applied by some vendor to what we here call material. In addition, there is the prospect of greater discounts when purchasing in large quantities.

In the graphs shown in Figs. 3 and 4, the curve for material reduction applying to raw material is given as a ninety-five percent curve (exponent of .0732). For purchased material this factor is shown at eighty-eight percent (exponent of .184). By purchased material is meant such items as wheels, oleo struts, instruments, engines and starters, and accessories of a nature usually procured from outside by airplane manufacturers. The change in factor to eighty-eight percent instead of ninety-five percent when comparing purchased raw material is brought about by the greater proportion of labor present in the former. The item of purchased material (and particularly for engines, propellers, and instruments) is, in reality, not truly represented by a straight line in quantities up to one or two hundred as shown in Fig. 3 and as used by an airplane manufacturer in that the purchased material vendor is the supplier to many airplane manufacturers and thus is constantly manufacturing in greater quantities than is the airplane manufacturer. It should also be noted that frequently the same purchased item is used several times in one airplane, further emphasizing the above principle. Nevertheless, if intelligent allowance of this fact is made for special cases, the curves may be used satisfactorily. In the preparation of actual estimates it is best to make a third material item of engines, propellers, and instruments using prices received from actual quotations only reduced by the amounts obtainable from discounts securable after negotiation with the vendor, noting however from the general principles of the curves, the nature of reductions in large quantities which it is reasonable to expect.

Overhead

The overhead, or burden, varies, within limits, with quantity. The exact amount fluctuates greatly for different cases, depending, for example, on whether a particular factory is engaged in the manufacture of one type of plane or of many types. The following relationship shows for one particular factory the type of overhead variation which maintains. When this factory was employing five hundred workmen, the overhead ran one hundred percent; at one thousand workmen, this was reduced to seventy-five percent; and at fifteen hundred workmen to sixty percent. It is probable that the curve would flatten out above that amount and then, in very large quantities, increase in amount. In combining factors of labor, material, and overhead to determine a suitable curve for direct application to the whole airplane, a figure of seventy percent for overhead has been used in this paper.

Complete Airplane

In Fig. 4 there is shown a curve for use in comparing the cost of the complete airplane in different quantities.

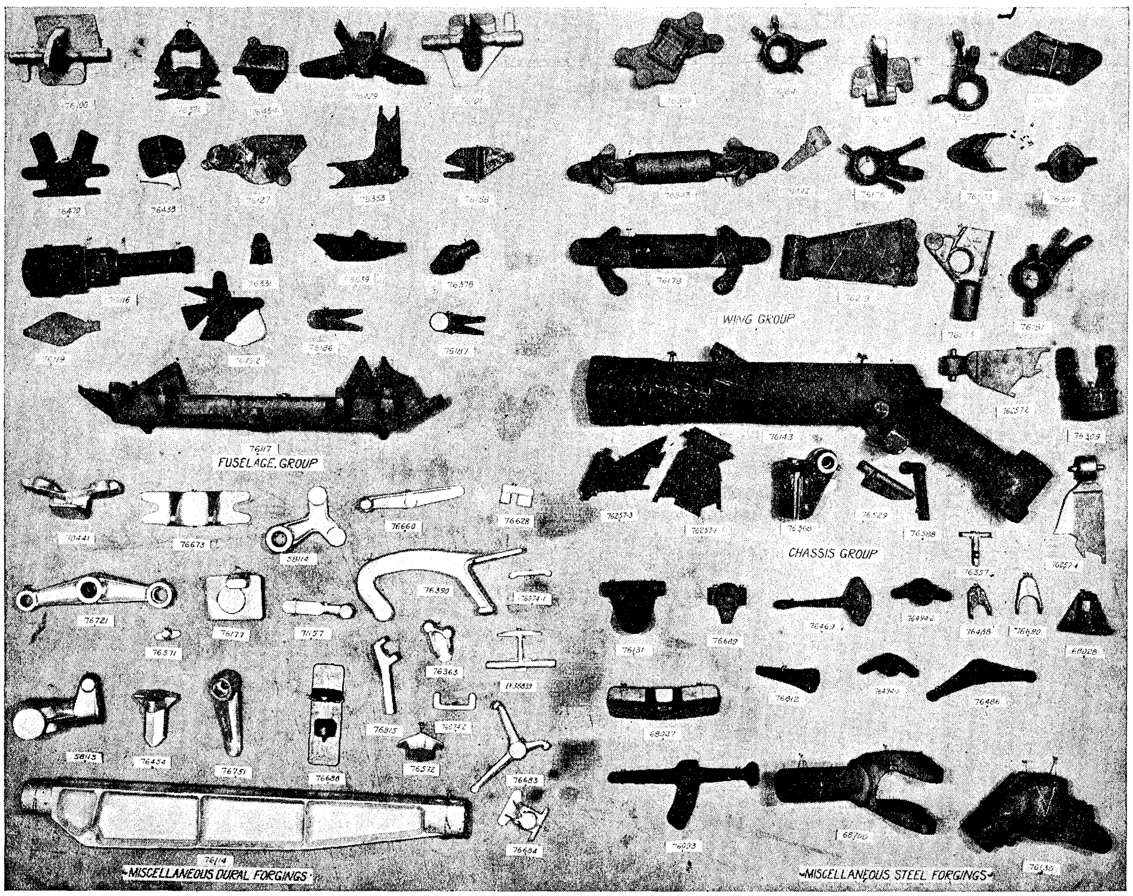


Fig. 5

A suitable relationship of labor, raw material, purchased material, and overhead has been used and by this method it is indicated that the curve will start out at eighty-three percent, then change to eighty-five percent, then change to eighty-seven percent, and finally reach ninety percent. This change in slope is an indication of the relatively greater importance of material to labor as quantity increases.

Non-Consecutive Orders

Considerable judgment is necessary when applying the curves here developed to succeeding orders of the same airplane. Consideration must be given to the changes introduced between these orders and, as well, the lapse of time which occurs. It is obvious that new set ups; re-establishment of tools; labor turnover between orders; necessity for making new purchases; all contribute towards higher costs for the second order than would maintain if it were combined at one time with an earlier one. Judgment must therefore be used in selecting the proper factor when estimating the costs for such succeeding order. In general, and as an indication of procedure, the factor for the new order would vary from a factor proper for a quantity which equals the quantity of the new order plus eight-tenths of the quantity of the old order, to the factor for a quantity represented by the new order only if, in this case, the airplane has been out of production for a long time.

Unit Cost

It is interesting to consider the cost per pound of structure or of airplane light weight (including engine, propeller, instruments, etc.) which now maintains and which may be expected to maintain when producing in increasing quantities. In quantities with which we are so far familiar, it appears that the *structure* of an airplane made by stick-and-wire-and-fabric or welded steel-fabric construction ranges from about three and one-half to four and one-half dollars per pound and for the *whole airplane* (light weight), including engine, propeller, and instruments, this figure ranges from four to five dollars per pound, in a quantity of twenty-five in each case. These figures for all-metal airplane construction range, for the *structure,* from five and one-quarter to six and one-quarter dollars per pound, and for the *whole airplane* (light weight), from five and three-quarters to six and three-quarters dollars per pound. These latter figures for an all-metal airplane would reduce to about two and one-half and two and three-quarters dollars per pound in a quantity of one thousand. For one hundred thousand units (if we may be pardoned for mentioning a figure so out of keeping with experience to date) these values, respectively, would reduce to one dollar and one dollar and twelve cents per pound. It is interesting to compare this figure with the present cost of materials only ranging from just under one dollar per pound to about one and one-quarter dollars per pound as previously derived. The range of figures here mentioned are roughly applicable to all sizes and functions of machines, from the small two-place private owner plane to the large transport. However, note should be made of the fact that in quantity extensions it is the small plane for which the extremely large productions may be anticipated in spite of the fact that at present larger productions for transport planes than for the small ones maintain.

Also, it should be noted that other factors enter in when consideration is given to the unit cost of military planes constructed to government specifications and under government supervision. Numerous comparisons made in the past indicate that in this case the cost per pound when compared to equivalent weight of material for a commercial customer, has increased under government contracts by never less than fifteen percent and in certain cases to as much as thirty-five percent, averaging perhaps twenty percent. This increase is occasioned by the added complexity of the product; the need for following government specifications, handbooks, manuals and general requirements; the loss of smooth engineering and factory operations through government inspection requirements and the delays in receiving approvals of analyses, tests, drawings, and parts.

Let us now determine by actual example the anticipated variation in price with quantity. For the purpose we may select a two-place airplane somewhat along the lines of the specifications used by the Bureau of Air Commerce in recent purchases. The general specifications in the present example are as follows:

Useful Load	700 lbs.
Light Weight	1100 lbs.
Gross Weight	1800 lbs.
Structural Weight	800 lbs.
Engine	100 to 125 h.p.
High Speed	125 to 150 m.p.h.
Speed Range	3
Material	All-Metal

Price Estimate in a Lot of 25

Cost—1,100 lbs. (Light Weight) @ $6/lb.	$6,600.00
Profit (manufacturing, at 10%)	660.00
Sales Discount (20%)	1,815.00
Price	$9,075.00

(Use $9,000, as engine price will be lower in small quantities than is assumed in $6/lb. unit cost used above for light weight.)

Chart of Price Variation

Quantity	25	100	500	1,000	10,000
Factor (%)	.43	.29	.20	.168	.10
Price ($)	9,000	6,070	4,180	3,520	2,090
Price per lb.	8.18	5.52	3.80	3.20	1.90

We thus see that for a plane of these specifications and in the original quantity cited by the Bureau of Air Commerce when commencing its $700 Small Plane program, would have to be priced at about three hundred percent more than was hoped. Perhaps some reductions from the estimate could be effected by altering construction, design, and reducing sales discounts and profits (although by so doing the ten thousand units would probably never be sold) but in the quantity of ten thousand units which is under consideration, it is doubtful whether a price of less than $1,750 could possibly be attained.

Let us now see what may be expected in the class of plane more nearly comparable in useful load to our present family automobile to ascertain what deductions seem justifiable. The general specifications of such a plane might be as follows:

Capacity	4–5 Place
Useful Load	1400 lbs.
Light Weight	2200 lbs.
Gross Weight	3600 lbs.
Structural Weight	1600 lbs.
Engine	300–400 h.p.
High Speed	175–200 m.p.h.
Speed Range	3
Material	All-Metal

In estimating the price in a lot of twenty-five, we may assume a price just twice that used for the previous example as the light weights bear that relationship:

Chart of Price Variation

Quantity	25	100	500
Factor (%)	.43	.29	.20
Price ($)	18,000	12,140	8360
Unit Price ($/lb.)	8.18	5.52	3.80

1,000	10,000	100,000	250,000	1,000,000
.168	.10	.07	.061	.05
7040	4180	2930	2550	2090
3.20	1.90	1.33	1.16	.95

Let us now see where the automobile stands as to price in approximately these quantities:

Price ($)	4,700	1,200	1,000	750	650
Weight (lbs.)	6,000	3,700	3,400	3,250	2,900
Unit Price ($/lb.)	783	.324	.294	.231	.224
Ratio of Unit Prices:— Plane to Automobile	4.1	5.86	4.53	5.02	4.28

Some conclusions from a study of this comparison are of interest, even though the values are extremely approximate in nature.

First, it will be noted that the downward trend in prices of cars with quantity indicates a curve relationship approximating that used for the plane, as shown by the fairly constant ratio of costs per pound in different quantities which maintain. This ratio averages about 4.75. This increase in unit cost of 475% for the plane over the car is occasioned by three causes: the improvement in weight saving of fifty percent as indicated by comparing light weights (2200 lbs. vs. 3300 lbs.) with the attendant design refinement and more expensive construction; next, the increased complexity inherent in three dimensional vs. two dimensional operation, which necessitates more controls, more strength stipulations and the use of seventy-five horsepower per person against about twenty-five; and finally, by the greater efficiency in designing cars to low cost because of the vast backlog of experience in the art not yet acquired or directly applicable to planes in large quantities. In this last item lies the hope of "beating the curves" if and when we get into large production.

The account is not all one-sided however, as will be seen by examining performance. In fact a true evaluation of the saving in time, in an age wherein this factor is of ever increasing importance, should and, it is believed will, throw the balance the other way for many uses. The plane has a cruising speed of three times that of the car (175 vs. 57 m.p.h.) and, when comparing time saving in making a trip between points three hundred air miles apart, is five times superior (300 air miles at 150 m.p.h. equals 2 hours as against 400 road miles at 40 m.p.h. equals 10 hours). Only time can prove just how valuable time saving is to mankind.

Market

All of the foregoing, in reality, has been carried through in an effort to establish the market possibility which price reductions will make feasible. We have the usual circle of relationships wherein price can be reduced most effectively by increasing quantity but wherein quantity production can only be obtained through market possibilities brought about by cheaper prices.

Simplicity and cheapness of design will make possible gradual reductions in prices which will make possible the sale of somewhat greater quantities with cheaper prices brought about by virtue of such quantity increase. The desirable cycle of events can be given greatest impetus by improving the product which means improvement in performance efficiency and safety, so as to make it possible to offer the public something really worth while. As the benefits of flying are more and more realized because of the use by the public of airplanes of surpassing performance and far greater safety, the possibilities of market extension alluded to will be realized.

Acknowledgment is made of the great assistance during the past fifteen years rendered by my associates, Mr. E. Bertran, Mr. F. W. Devlin, and Mr. J. A. Williams.

Chart of Price Variation

Assumed Airplane—Specifications

Capacity	4–5 Place.	Engine	300–400 h.p.
Useful Load	1,400 lbs.	High Speed	175–200 m.p.h.
Light Weight	2,200 lbs.	Speed Range	3.
Gross Weight	3,600 lbs.	Construction	All-Metal.
Structural Weight	1,600 lbs.		

Unit Airplane Prices

Quantity	25	100	500	1,000	10,000	100,000	250,000	1,000,000
Factor (%)	.43	.29	.20	.168	.10	.07	.061	.05
Price ($)	18,000	12,140	8360	7040	4180	2930	2550	2090
Unit Price ($/lb.)	8.18	5.52	3.80	3.20	1.90	1.33	1.16	.95

Rough Automobile Data

Weight (lbs.)	6,000	3,700	3,400	3,250	2,900
Price ($)	4,700	1,200	1,000	750	650
Unit Price ($/lbs.)	.783	.324	.294	.231	.224
Ratio of Unit Prices Plane to Auto	4.1	5.86	4.53	5.02	4.28

Notes:

1—Average Ratio Unit Price Plane to Auto is about 4.75.
2—Small fluctuation from average Unit Price Ratio indicates similar auto production curve.
3—Airplane has greater weight economy (50% lighter than auto).
4—Airplane has 75 h.p. per person, Auto 25.
5—Plane Cruising Speed vs. Auto equals 175/57=3:1.
6—Plane Block-to-Block Time for 300 air miles vs. auto equals 10 hrs./2 Hrs.=5:1.