MAINTENANCE COST STUDIES OF
PRESENT AIRCRAFT SUBSYSTEMS

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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PART I - A METHOD FOR OBTAINING MAINTENANCE COST ESTIMATING RELATIONSHIPS FOR AIRCRAFT SUBSYSTEMS

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ABSTRACT

This report describes two detailed studies of actual maintenance costs for present transport aircraft. The first part describes maintenance costs for jet transport aircraft broken down into subsystem costs according to an ATA classification. From 90 airlines polled, only four were able to supply costs in this breakdown. Despite the lack of data, multiple regression techniques were then used to demonstrate the construction of cost estimating formulae for both subsystems and a total aircraft system. The results indicate the possibility of improving present methods of estimating maintenance costs.

The second part of this report briefly describes the results of an extremely detailed study of actual maintenance costs for the rotor and transmission systems of present commercial helicopters. The background information concerning each item of maintenance cost was examined to determine if it would be avoidable in the context of a mature airline operation with a full scale modification program for vehicle deficiencies.
The results show that if only "normal" maintenance on rotor and transmission systems were performed, the potential maintenance costs for present helicopters are roughly 1.3 times the standard ATA estimate for fixed wing aircraft.
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I - INTRODUCTION

The purpose of this study is to develop a technique for producing a maintenance cost formula which will reliably predict costs for a wide range of airborne vehicles. The technique is to subject a volume of cost data for each aircraft system to multiple regression analysis. The value of its statistical basis is twofold. On the one hand it eliminates any personal bias that creeps into formulation to satisfy "intuitive" trends, while on the other hand the ever growing volume of statistics can be utilized in some continuous updating fashion to modify the formula and maintain it in as valid a state as the source data itself.

The rapid rate of growth of the U. S. domestic and international air transportation industry, together with the vast potential for growth which lies ahead, have established the need for accurate economic forecasting as an essential managerial tool. The industry has been fortunate in two respects. First, the Civil Aeronautics Board (CAB) has, through the reporting system demanded by CAB 41, introduced an element of standardization in
accounting for U. S. Carriers, thereby ensuring much useful statistical cost and traffic data so essential to good forecasting. Second, since 1944 the ATA Direct Operating Cost Formula with its various modifications has, despite its limitations, served as a reasonable forecasting tool, enabling individual airlines to compare the Direct Operating Costs (DOC) of different aircraft operating on given routes.

It is customary to define direct operating costs as those associated with

Operating Crew
Fuel and Oil Consumption
Vehicle Insurance, Public Liability and Property Damage
Direct Maintenance
Depreciation

Except for direct maintenance, all these costs are either defined by crew contracts, performance specifications, insurance rates and the market price of fuel and oil, or are prescribed in some fashion by assuming a depreciation period, a residual value, and a percentage spares holding. An airline would have no difficulty in accurately forecasting the cost of these elements for a new vehicle this
year and next year. No such accuracy is possible with forecasting maintenance costs which represent from $1/5$ to $1/3$ of the total direct cost.

For this reason the specific area of maintenance costs was selected for special study and the application of multiple regression analysis.
The two formulas in wide use today are the 1960 revision of the ATA "Standard Method of Estimating Comparative Direct Operating Costs of Transport Airplanes" and the November 1959 issue of the SBAC "Standard Method for the Estimation of Direct Operating Costs of Aircraft."

Let us examine the direct maintenance portion only of the ATA formula, converted to dollars per block hour, given by the following four expressions:

1. **Labor - Aircraft and Other**
   
   
   \[ \text{$/block hour} = 1.03 \ (K_{LA}) \ (R_L) \Rightarrow a_1 + b_1 \ (WA) \]

2. **Labor - Engines**
   
   \[ \text{$/block hour} = 1.03 \ (K_{LE}) \ (N_E) \ (R_L) \Rightarrow a_2 + b_2 \left( \frac{T \ or \ SHP}{TBO} \right) \]

3. **Material - Aircraft and Other**
   
   \[ \text{$/block hour} = 1.03 \ K_{MA} \Rightarrow a_3 + b_3 \ (CA) \]

4. **Material - Engines**
   
   \[ \text{$/block hour} = 1.03 \ (K_{ME}) \ (N_E) \Rightarrow a_4 + b_4 \ (CE) \Rightarrow a_5 + b_5 \ (TBO) \]

where

\[ K_{LA} \] is the man hours per block hour required for aircraft and other, and is assumed to increase
linearly with the empty weight of aircraft minus engines (WA)

$R_L$ is the labor rate ($3$/hour in the 1960 revision)

$N_E$ is the number of engines

$K_{LE}$ is the man hours per block hour required for engine. For a given Engine TBO (Time Between Overhaul) this is assumed to increase linearly with engine take-off thrust or equivalent shaft horsepower (T or SHP)

$K_{MA}$ is the material cost per block hour for aircraft and is assumed to increase linearly with the cost of aircraft less engines. (CA)

$K_{ME}$ is the material cost per block hour for engine. It is assumed to increase linearly with engine cost, and inversely with attained engine TBO. (CE, $TBO^{-1}$)

A later chapter will discuss the sources of maintenance costs. It suffices here to pinpoint a few, in order to demonstrate the inadequacy of the present ATA formula.

Let us, for example, examine the influence of weight. It has become very popular for aircraft manufacturers to
offer a range of vehicles within a given family to meet the peculiar demands of different airlines. The principal difference is in fuselage length, and associated with it come certain structural and performance differences. But as far as systems are concerned, there is a large area of compatibility between the aircraft. In fact, this closeness is a strong selling point because it allows airlines with a mixed short, medium and long-range route structure to match vehicles more closely to their optimum ranges and yet benefit from the common features of the family with low spares holdings, common maintenance practices, standard crew compartments and uniform ground servicing and handling equipment. Since maintenance cost derives from these common areas, there should be no significant difference in costs between members of the same aircraft family despite the variation in their empty airframe weight.

There is another instance where the units carried (and therefore the hourly costs) are unrelated to the weight or size of the aircraft. The communications and navigational equipment carried on both large and small transports is dictated by the route flown, so that the
contributions from these systems to the total maintenance cost are independent of empty airframe weight.

When we come to the manner of operation, no provision is made to account for systems, such as landing gear, where different values of landings per flight hour have an obvious influence on maintenance costs.

Route structure, traffic schedule, utilization, type of maintenance scheme, and fleet size have a direct bearing on the size of the labor force and hence on the maintenance cost, yet none of these appear in the formula.

In short, as valuable as the ATA formula has been, its limitations in the maintenance cost area have prompted the move to introduce a more radical modification that would both account for conventional types in a more accurate manner and also enable its use for VSTOL and supersonic transports. One approach by a group at Lockheed, under the direction of Mr. R. F. Stoessel, is outlined in a proposal entitled "More Realism in a Standard Method for Estimating Airline Operating Expense." In this proposal cognizance is given to the need for adding relevant parameters, and also to the varying characteristics of different aircraft systems. In the interest of simplicity,
seven major groupings are retained, each contributing two labor costs, one on a flight hour basis and the other on a flight basis, and two material costs on similar bases. The parameters are limited to cost of airplane, basic empty weight of airframe, level flight cruise Mach number, cost of engine, number of engines, thrust or shaft horsepower, number, cost and weight of propeller.

What is not clear is how the philosophy and the cost data were manipulated to obtain the final formulas. In addition, some of the shortcomings demonstrated for the ATA formula still apply.

The technique proposed in this study has the following advantageous features:

1. The use of multiple regression is a mathematical tool for processing data in an unbiased manner (unless a bias command is deliberately introduced).

2. By applying regression to individual systems, there is a greater expectation of highlighting the parameters most expressive of the peculiarities of that system. And whereas such parameters
may well stand out on the system level, they might be overshadowed or entirely missed if the regression were applied at the total costs level.

3. The ATA system breakdown is nothing more than a subdivision into logical, well defined, separate functions. There may well be differences between the design philosophy of a hydraulic system on two different aircraft, but in both cases the function will be the same, to provide some kind of hydraulic fluid at some pressure. Therefore the influential parameters are likely to be the same for the two aircraft, so that the final choice of parameters by the regression process is likely to be correct.

4. There is a certain elegance in a formula which is self refining, and where the continuously growing past, together with the immediate present, combine in just the right measure to produce a balanced prognosis of the future. True, some investment would be needed to
establish conformity of definition among participating airlines, and to introduce the administration that would culminate in a flow of correctly punched data cards from airlines to a central data bank. However, once operating, it would involve a minimal expense, as the airlines in any event need to summarize costs, and what better way than through a system which provides them with a datum from which to gauge their own performance.

All that the central processor would be required to do is to add the cards to the existing data deck, adjust certain values on some of the control cards to account for the increased number of observations, and run the program through the computer to produce the latest formula coefficients. Examination of the regression criteria would establish whether there was a need to change any of the independent variables. Of course, with more observations, more independent parameters can be tested.
Again, because the ATA system breakdown is an expression of the vehicle's functions, retaining individual system regression equations makes the task of estimating maintenance costs of future technology vehicles much simpler. For one thing, wherever a system does not exist, comparing functions can help in estimating which of the parameters needs extra weighting and which needs less. As for entirely new systems, it should be possible to draw comparisons from the existing ATA systems, and thereby build up a cost estimate. The synthesis of all these sub-costs is likely to give a more accurate estimate of total maintenance costs than by attempting estimates with the gross formula as a starting point.
III - THE REGRESSION MODEL

The underlying assumption throughout this paper asserts that there is a relationship between the cost to maintain an aircraft system and certain independent variables which characterize that system. The regression model is a technique for calculating the coefficients of those variables and for indicating how successful was the choice in matching observation to formula.

We assume that there is a definite relationship

\[ y = \lambda + \beta_1 x_1 + \beta_2 x_2 + \ldots \beta_r x_r \]

where \( y \) is the dependent variable - in our case \$/flight hour

\( \lambda \) is a constant

\( \beta_1, \beta_2, \ldots, \beta_r \) - are coefficients

\( x_1, x_2, \ldots, x_r \) - are our choice of independent variables (e.g., utilization, hours per landing). In fact, our observed value of \( Y \), which we label \( Y_j \), differs from the theoretical by some error term \( U_j \), and since we do not know what the \( \lambda \) and \( \beta \)'s are, we are attempting to estimate them from our knowledge of the \( Y_j \)'s and our supposition as to the \( x \)'s. We are claiming in effect that
\[ Y_j = a + b_1 x_{1j} + b_2 x_{2j} + b_3 x_{3j} + \ldots + b_r x_{rj} + U'_j \]

where \( Y_j \) is the value of the dependent variable (\$/flight hour) for the \( j \)th observation, 
\( a \) is the estimate of the constant 
\( b_1, b_2, b_3, \ldots, b_r \) are the estimates of coefficients 
\( x_{1j}, x_{2j}, x_{3j} \) respectively, are the values of the independent variables applicable to the \( j \)th observation. 
\( U'_j \) is the residual - the difference between the observed value \( Y_j \) and the estimated value.

Whenever the number of observations \( n \) is greater than the total number of variables (independent plus dependent) it becomes necessary to define what is meant by the best fit to the input data. In this study, it is given by those values of the coefficients which minimize the sum of the squares of \( U'_j \), hence, the term "least squares regression analysis".

A computer program developed by the University of California (and adapted for use on the MIT 7094) performs the calculations necessary to the evaluation of these coefficients and provides the associated material for judging the "goodness" of fit.
Basically they are developed out of the following relationships: Since

\[ U'_j = Y_j - a - b_1 x_{1j} - b_2 x_{2j} - b_3 x_{3j} \ldots - b_r x_{rj} \]

Then

\[ \sum_{j=1}^{n} (U'_j)^2 = \sum_{j=1}^{n} (Y_j - a - b_1 x_{1j} - b_2 x_{2j} \ldots - b_r x_{rj})^2 \]

If we want the value of \( a \), for example, which minimizes the value of \( \sum (U'_j)^2 \), this is obtained from

\[ \frac{\partial}{\partial a} \left[ \sum (U'_j)^2 \right] = 0 \]

i.e.,

\[ \frac{\partial}{\partial a} \left[ \sum (Y_j - a - b_1 x_{1j} - b_2 x_{2j} \ldots - b_r x_{rj})^2 \right] = 0 \]

or

\[ \frac{\partial}{\partial a} \left[ \sum_{j=1}^{n} \left( Y_j^2 + a^2 + b_1^2 x_{1j}^2 + b_2^2 x_{2j}^2 + \ldots - 2aY_j + 2ab_1 x_{1j} + 2ab_2 x_{2j} + \ldots \right) \right] = 0 \]

\[ 2an - 2 \sum_{j=1}^{n} Y_j + 2b_1 \sum_{j=1}^{n} x_{1j} + 2b_2 \sum_{j=1}^{n} x_{2j} + \ldots + 2b_r \sum_{j=1}^{n} x_{rj} = 0 \]

Therefore

\[ a = \frac{1}{n} \sum_{j=1}^{n} Y_j - \frac{1}{n} \sum_{i=1}^{r} \sum_{j=1}^{n} b_i x_{ij} \]

In a similar manner, the expression which gives the values of coefficients \( b_k \) that minimize the value of \( \sum (U'_j)^2 \) is given by
\[
\sum_{k=1}^{r} \sum_{j=1}^{n} b_k x_k x_j + a \sum_{j=1}^{n} x_{kj} - \sum_{j=1}^{n} x_{kj} y_j = 0
\]

Calling \( \sum x_{kj} (y_j - a) = \sum x_{kj} z_j \)

This gives, in Matrix form

\[
\begin{bmatrix}
(\sum x_k x_j)
\end{bmatrix} \cdot \begin{bmatrix} b_k \\
\end{bmatrix} = \begin{bmatrix}
\sum x_{kj} z_j
\end{bmatrix}
\]

and there are standard computer techniques for solving such matrix equations to give the values of \( b_k \).

Engineers are familiar with graphical representations of two variables, and also of three variables, only two of which may vary simultaneously. The great quality of the regression tool is that it allows \( r \) variables to vary simultaneously, where

\[ r \leq n-1 \]

\( n \) being the number of observations.

The bridge between the precise regression theory and the real world is in the choice of data that is fed into the computer, and in the interpretation of the results that emanate from it.
Choice of Data

There are a number of guidelines to the selection of characteristic parameters governing the input data.

First, they must be the cause and not the effect.

Second, they must be attainable and measurable.
Worker morale, for example, may well have an influence on the labor content of a maintenance item, but there is no point in choosing it as a parameter unless it can be expressed in measurable terms.

A device does exist which enables the true weight of some significant but immeasurable parameter to influence the final cost formula. This is the use of the dummy variable. The data of this study is quite limited, with a maximum of nine observations; of which two are helicopter airlines. There is clearly some difference between the kind of costs reported for the conventional aircraft and those for the helicopters, that is not accounted for by any of the intuitive variables. A dummy variable is introduced, helicopters being given a value 1 and conventional vehicles 0. If the coefficient of this variable is entered into the regression equation, it has the effect of altering the value of the constant term by this amount for helicopters only. It does not explain
the difference, it merely accounts for it. More will be said on the use of dummy variables when discussing the selection of parameters for the individual aircraft systems.

Third, the parameters chosen must be distinct or orthogonal. The cost of maintaining structure (ATA 51-57) may show a dependence on fuselage length and number of seats, simply because it is a function of size, and both of these parameters express size. One only should be used.

Fourth, since a linear regression model is being used, instances where it may be obvious that no such linear relationship exists need special treatment, as explained a little later.

Fifth, the variance of error terms should be independent of the size of the explanatory parameters (homoscedasticity).

The dependent variable does not have to vary linearly with the independent parameters. Each \( x_{ij} \) may, in fact, be representing a variable to any power, or the log of the variable. The simplest, of course, is the linear model, and this is the one used here. The aim must certainly be to obtain a simple forecasting tool, but not
at the expense of accuracy and considerable judgment is needed when studying the results to decide the optimum.
The BMDO2R Stepwise Regression Computer Program

The specific computer program used in this study to evaluate the coefficients and constants of the regression equations is the Bio Medical Computer Program BMDO2R. It computes them in a stepwise manner, one variable being added or removed at each step. It chooses that variable which makes the greatest contribution to reducing the error sum of squares, and it decides this from the F values of the variables.

It is essential to understand the significance of some of the quantities that are printed out at each step in order to analyze the results and judge the merits of each equation. Multiple R is the multiple correlation coefficient which ranges in value between 0 and 1.0. In general, where the number of observations is large, both absolutely and relative to the number of independent variables, the residual degrees of freedom will be large in number and therefore a high R value will be equivalent to a low standard error of estimate, both indicating that the regression line that has been computed succeeds in explaining the data points very well. The reverse is also true.

However, as the number of residual degrees of freedom decreases to the level reached in this study (1, 2 and 3) so does the confidence level in the results diminish, and this
has been one of the problems.

Standard Error of Estimate gauges the amount of residual error between the data points and the computed regression line, and is also weighted by the presence of the residual degrees of freedom which lowers the confidence level when this number is small.

F-to-enter is a guide as to how well the addition of the relevant variable to the regression equation could help in making the fit a better one. The higher the value, the better the fit, and vice versa.

F-to-remove is a guide to the program that a particular variable is not contributing very much to the ability of the regression equation to fit itself to the data points. Wherever it falls below a value that may be prescribed, it is transferred back to the original variables not yet in the equation.

The maximum number of steps is, of course, governed by the number of variables that are permitted. The minimum number of steps is controlled by placing limits on the F level for inclusion or deletion. In this study F values of 0.5 and 0.3 respectively were used. If any of the variables not in the equation have an F value higher than 0.5, they will be candidates for entry into the
equation, the one with the highest F-to-enter being chosen. If none of the F-to-enter values exceeds 0.5, the computation stops. If a variable inside the regression equation has an F-to-remove value lower than 0.3, it will be transferred back to the variables not yet entered.

One valuable asset of this program is the option to force variables into the equations rather than allow the program to pick its own way through the variables based on F value criteria. This power to override is obtained by the use of a special control card that has a range of coded numbers from 1 to 9 which mean the following things:

1. Delete this variable, or this is the dependent variable.

2. This is a "free" variable, and the program is to use just F criteria to include it in, or exclude it from, the regression equation.

3. This is a "forced" variable, at a low level, and will definitely appear in the equation if the tolerance test is passed.

9. This is the highest level "forced" variable, with numbers 3 to 9 being graded accordingly. A variable with this coding will enter the equation first.
The order of advancing from step to step is:

a) If there are one or more independent variables in the regression equation with a control value of 2 (free variables), and an F value less than the prescribed "F-to-remove" limit, the one with the smallest F value will be removed.

b) If a variable is removed by (a) and there are one or more independent variables, not in the equation, which pass the tolerance test and have a control value of 3 or more (forced variables), the one with the highest control value and F value will be added. The tolerance level is prescribed on a control card.

c) If no variable is removed by (a) or added by (b) and there are one or more independent variables not in the equation which pass the tolerance test, have a control value of 2 and an F value greater than or equal to the F-to-enter value specified on a control card, the one with the highest F value will be added.

If no variable is added or removed, the computation terminates.
IV - MAINTENANCE REPORTING AND ACCOUNTING PROCEDURES

The ATA 100 standard method of presenting technical information includes a well-defined breakdown of systems that has gained acceptance not only by aircraft manufacturers and operators in the U.S. but also in most of the non "iron-curtain" countries where American manufactured aircraft are operated. Maintenance, overhaul and operations manuals are sectioned in accordance with it; modification leaflets, service bulletins, information letters all follow suit. A description of the system coding is given by the columns of Table I.

Unfortunately, very few airlines at present record their costs of maintenance by this classification, or indeed by any other accepted standard, with the exception of the CAB format which demands a breakdown by

- Airframe labor
- Airframe material
- Engine labor
- Engine material
- Total direct maintenance
- Applied burden

The success of any method which bases itself on the manipulation of statistical data is bound up with the volume
and the accuracy of such data. It is therefore to be hoped that there will be wider acceptance of this ATA costing classification, particularly since individual airlines stand to gain by so doing. By adopting the same unified costing basis that is the foundation of the formula, the airline will be able to measure the level of its own costs against a standard and, from a knowledge of the influential parameters, should be capable of some degree of control.

The growing usage of computers presents an excellent opportunity to change over to this costing classification. Certainly a great deal of misinterpretation can be avoided at the same time since much of the classification can be built into the administrative procedure, without requiring individual mechanics to decide the correct system allocation.

All scheduled labor and material costs can be covered in this manner. Even unscheduled material costs need not depend on the mechanic's judgment since the total inventory would be automatically recorded. Even if the same part is used in more than one system, an appropriate dash number would indicate the particular system being worked on.
This leaves just the classification of unscheduled labor to be determined by the individual mechanic, a much lesser administrative problem than at present, with smaller risk of distorting the system cost. The importance of ensuring that the costs reported by one airline on a system encompass precisely the same components as those included by another airline is paramount. Furthermore, accounting procedures need to be standardized so as not to introduce distortions into the calculations of hourly costs.

By following the ATA aircraft system breakdown, the area of possible misrepresentation will be narrowed down. A constant-speed-drive oil cooler will be correctly assigned to system 24 - Electrical Power - and not to 71 - Power plant - even though the unit may be an integral part of the power plant, removed together with it and processed through the power plant repair and overhaul shop. Nor does this necessarily involve shop people in more non-productive administrative routines. It does mean that the paper work that in any case keeps track of shop work is coded in some way as to be tied to the correct ATA system to which the cost will ultimately be allocated. There are bound to be those areas where it would be just as logical to classify a unit under one system as under another, and this is the
reason that an organization such as the ATA would be ideally suited to centralize the activity. The technical committee would make the arbitrary decisions which the member airlines would be bound to accept.

The same kind of centralized decision-making is required in the case of accounting. Let us examine, for example, the manner of obtaining the cost per flying hour due to airframe overhaul. Because the TBO of airframe overhauls is now quite high (8000 to 12000 hours), even with a high utilization of 4000 hours per year this does not demand more than one overhaul every 2 years. Some airlines elect to perform overhauls in this fashion. In particular, an airline with a few large fleets may prefer to do one fleet as a batch one year and another fleet as a different batch another year, with a permanent team of trained men, specialized equipment and dock arrangements. Another airline, perhaps with a smaller fleet, but with winter or summer seasonal traffic, may prefer to break up the work content into equal yearly quantities which would ground every aircraft of the fleet for a specific period during the off-season. Yet a third airline, capable of scheduling a high utilization throughout the year, finds it more economical overall to perform the work
by subdividing it into portions small enough to be performed during the more frequent routine checks.

In the first case, one would have to wait two years to obtain true costs, which should be apportioned to the total flying hours accrued since new or since the last overhaul. It would be false during the interim year to assign a reserve allocation in lieu of real costs simply to supply the processing agency with data.

In the second case, there would be true costs to allocate to a year's operation, and there would be justification for submitting this data. However, at the end of the overhaul cycle, the total cost should be apportioned over the total flying hours of the cycle, to account for one overhaul block being light and another being heavy. The same reasoning would apply to the third case.

It would be the task of the centralized agency to standardize the accounting, as far as maintenance costs are concerned, and to make the necessary arbitrary decisions that have no particular importance for the airlines, but have very great importance in the assembly of consistent data.
When an airline reports a system cost, what is included? It is clearly not a precise accumulation of every cost that could be associated with that specific aircraft system. Routine checks for example are normally carried out by zones, in which case several aircraft systems would be undergoing checks more or less simultaneously and it would be extremely difficult to extract the manhours appropriate to each system. Thus routine checks generally appear as a separate cost item.

Some airlines do not even include turnaround checks and enroute maintenance as a direct maintenance cost. Most consider the labor of inspectors as an overhead and not direct labor.

What expenditures are then categorized as Aircraft System Costs?

1. All labor and material costs associated with the scheduled or unscheduled removal of a component, its overhaul, repair or readjustment are generally recorded by special job numbers and there is no problem in assigning costs to the appropriate ATA system.
2. Labor and material costs of installing modifications are capable of direct assignment to an ATA system, since these too are generally covered by specific work orders.

3. Repairs to the airframe structure present no difficulty in being assigned to the correct ATA Structure system; although if a system such as control runs needs to be broken down to facilitate access, it is not clear which system would bear the burden of such disassembly, assembly and functional checkout.

4. Special checks are capable of correct assignment with the same proviso as in paragraph 3 above.

The costs which have been used in this regression analysis are assumed for the purposes of this study to be compatible, although the marked discrepancy in the figure for routine checks and maintenance of airlines A and B (Table III) leaves doubt, at least as far as this classification is concerned. (For this reason, in fact, this data from these two airlines was not used.)

Costs of systems 21 to 38 inclusive are treated as separate individual systems. In the interest of simplicity,
and because there is a strong affinity in any case, systems 51 to 57 inclusive are treated as one entity to cover aircraft structures, and systems 71 to 80 inclusive are grouped to represent combined engine and power plant costs. Except for systems 83 - accessory gearbox, 61 - propellers and rotors, and 84 - helicopter transmission, all other systems have been grouped under Routine Checks and Miscellaneous (RCM). This latter includes general aircraft handling, the smaller preflight, layover and turnaround checks carried out by line maintenance personnel, as well as the routine checks up to and including aircraft overhaul. It is as well to note that there is not too good an agreement between airlines on what this does include.

Applied burden is a cost item classified by the CAB, and although an indirect cost, is generally treated as if it were a direct cost. It includes the expenses of the administration of maintenance, and is so closely bound up with the direct maintenance cost that it too should be subjected to regression analysis.

Comments on the compatibility and value of the actual input cost data are given in Chapter VI.
VI - CHOICE OF AIRCRAFT SYSTEM PARAMETERS

There are three classes of parameters which are to be taken into account: those which characterize the airline; those which describe the characteristics of the particular system; and those which illustrate the manner of operation.

**Airline Characteristics**

1) **Fleet Size**

Certain economies in operating costs arise from increasing fleet size. Spares holding per aircraft, for example decreases, but this is reflected in decreased depreciation and not in maintenance cost. A certain minimum labor force is usually required in shift work, to include certain skills which could adequately meet the needs of a larger fleet. In particular, very definite economies ensue when the fleet size is large enough to warrant a permanent group of mechanics engaged solely on aircraft overhaul, for their familiarity with the tasks and the problems encountered lead to time saving techniques, experience, and devices. Fleet size is therefore a parameter likely to be applicable to all systems, particularly so for systems where the labor content is high.
2) **Utilization**

Any cost which is a function of calendar time rather than operational time will benefit from higher utilization, since a fixed cost is being spread over a greater number of flight hours, thereby reducing the dollars per flight hour. It is common to find checks and overhauls of safety and electronic equipment established on a calendar basis.

The influence of utilization on the cost of major airplane overhauls has been touched upon in Chapter III. If there is no seasonal characteristic to the airline operation, then it would be uneconomical to bring an aircraft in for its major overhaul at a lesser number of flying hours than the permissible, and in this event utilization has no influence. If, however, there is a seasonal characteristic, then there is a very marked influence of utilization which can take two directions. Because the overhaul must be performed at a certain calendar time, the TBO of the airplane must be a simple multiple (1, 2, 3, etc.) of the annual utilization. The airline will naturally press to have the TBO increased to the next multiple and thereby reduce the hourly cost.
The airworthiness authorities, with a conservative caution, would probably prefer not to exceed a given TBO, leaving the onus of having to take a virtual cut-back on the airline. This would naturally increase the hourly cost above its potential.

There is the more subtle influence of utilization which comes into play with the airline that has no seasonal restrictions but wishes to maintain a very high utilization, and this it achieves by distributing the work content of its major check and overhaul over the routine basic checks, thereby avoiding having to ground the aircraft for any lengthy period. The penalty paid is in a higher man hour per flight hour requirement. This is because considerable preparatory work is necessary to grant access for structural inspections. Trim and fairings have to be removed, panels unscrewed, fuel tanks emptied and purged, control surfaces disconnected, etc. If the aircraft is on the ground for a complete overhaul, all trades can take advantage of the ease of access to perform their necessary inspections, functional checks, adjustments, repairs and replacements. If, however, ground time is limited, then the amount of
work that can be performed is limited because zones cannot physically accommodate more than a given number of mechanics. Thus the same panel may have to be removed several times during the airframe TBO to enable the different trades their individual access.

However, over and above the economic advantages that high utilization brings to the total operating cost, there is a compensating maintenance factor also, due to Parkinson's Law, where "work expands so as to fill the time available for its completion." Some inspections are so largely qualitative, and to some extent subjective, that the longer an aircraft remains on the ground for check, the greater the likelihood of coming up with the report of some defect, not necessarily in any way impairing safety. It will seem then that utilization by itself tells only part of the story, and that associated with this parameter should appear airframe overhaul period and a dummy variable to account for one of three schemes; yearly block overhaul; one-time complete overhaul; and continuous segmented overhaul.

3) **Reporting Year**

Most cost studies relate dollar costs to the value
of the dollar in a given year. Since there is a steady
trend for labor rates and material costs to increase
with time, and since it is intended to have the formula
accuracy improve with time by the accumulation of data
on a continuous basis, the reporting year should be a
parameter in the final cost formula.

4) Time since First Delivery

When a new type is introduced into an airline
operation, higher than normal costs may be expected
due to the inexperience of the maintenance personnel
and the lower than possible component overhaul periods.
The trend of both factors is to lower costs with the
passage of time, countered by the influence of wearout
and fatigue. A new aircraft belonging to the same
family as those already in service should, if anything,
prove to be less expensive on maintenance than those in
the fleet for several years, since it gains from the ex-
perience of the others in respect to check periodicity,
component lives and speed of trouble shooting. The cri-
terion then is the length of time since the first aircraft
of the family entered the airline.
5) **Airline Productivity Measure**

There is very definite recognition of the fact that two airlines operating precisely the same equipment in precisely the same manner will not arrive at the same maintenance costs. The difference will in part be due to the random nature of the cost elements, which would produce a different figure if the selfsame airline could repeat its operation over again. It will in part be due to certain characteristics of the airline, such as management quality, worker productivity, and even company morale. An attempt to take cognizance of these latter factors warrants some, even crude, measure of productivity in the formula.

The direct maintenance labor force required is a function of:

(a) the total number of aircraft from all fleets being maintained
(b) the hours flown per day, month, or year
(c) the size and complexity of the vehicles
(d) the periodicity of the check cycles
(e) the amount of work contracted to outside agencies.
To obtain a crude guide to the maintenance force required, we may ignore (e) and (d), express (c) in terms of seats available, and arrive at the quantity called

\[
\text{Seat hours} = \text{Total aircraft per year} \times \frac{\text{hours flown per year}}{\text{Total number of seats available on all fleets}}
\]

The productivity measure then becomes

Seat hours per year per maintenance employee.

6) **Dummy Parameters**

With so many aircraft types, airlines, and modes of operation serving as the diverse population for the statistical analysis, there are bound to be certain groupings which demonstrate an affinity that cannot be defined in measurable terms. For example, a set of data from a given airline has associated with it the peculiarities of that airline, part of which may be explainable in terms of the productivity measure, or fleet size, but part of which would be a conglomerate of morale, management, geographical location, fleet mix, etc., and difficult to measure quantitatively. Or, to take another example, it would be reasonable to assume that helicopter
costs as a set would show some attribute that conventional jets would not, for aircraft systems common to both vehicles. We have, in other words, some characteristic that has weight which ought rightfully to influence the regression equation, and yet we have no scale whereby to measure it. In these circumstances a dummy variable is introduced with just two possible values, a 1 or a 0. In the first example, all data from airline A would receive a value 1 for dummy variable DUMMY A, and all other airlines would receive an 0. In the second example, all helicopter data would receive value 1 for DUMMY B, and all conventional jet data would receive an 0. This is in fact equivalent to increasing the constant in the regression equation by another constant equal to the DUMMY B coefficient for the helicopter, and zero for other aircraft.

The value of this device for the regression technique is that it helps to eliminate distortion from the parameters that have meaning in a physical sense by shunting the distorting influence off to a parameter which may have meaning, but not in the physical sense.

The dummy variable is particularly useful in helping to absorb new data from a distinctly new "breed" of
vehicle, e.g., if and when jet lift and supersonic transports enter commercial service. The bulk of the data will be that of current aircraft, and until such time as a body of cost statistics has been built up for the new vehicles, and more has been learned about their operation, each type will have its own dummy variable.

Aircraft Characteristics

Of the numerous parameters that specify an aircraft, some will be applicable to all systems, some to just a number of systems.

1) Age of Type of Aircraft

Here is yet a third usage of "time" which differs from the previous two, and this is the time between the date of certification and the reporting year.

The early months and years of an aircraft type are associated with unreliability, high defect rates, early and premature removals, and modification action. All of these are high cost factors. Once modifications begin to take effect and experience leads to accurate trouble shooting and correct maintenance procedures, reliability improves; and with it overhaul periods increase, defect rates fall and costs come down. It has been shown in an
airline study\textsuperscript{2} that where parts have no definite wear-out characteristics, and this is generally so for complex units, the conditional probability of failure, and consequently the premature removal rate, remains fairly constant with increasing TBO. Thus the older the aircraft type, the less influence does this parameter have. Even if units do demonstrate wearout characteristics, costly items with long life are likely to be capitalized and will therefore not appear under maintenance costs, while inexpensive items and/or short life units should appear in the block overhaul costs.

2) \textbf{Components}

The repair and overhaul costs of rotatable components is a major contribution to the total maintenance cost. The factors which influence these costs are the number of units on the aircraft, the defect rate and premature removal cost of overhaul spares and labor requirements.

Number of components per system is an inaccurate measure of cost since one expensive component overhaul can be far more costly than ten inexpensive ones.

Defect rate is a suspect measure because it is difficult to define it precisely. And even if the reporting
of defects is a legal requirement, this is quite different from defect rate which requires the processing that many airlines prefer not to do. Unless a standard method were instituted, it would be better not to use defect rate as a parameter.

Premature removal rate is usually well recorded, but the difficulties arise when trying to establish just how many were confirmed and how many unconfirmed. However, this is at least easier to define than defect rate and could serve as an independent variable.

Overhaul period is a good measure and readily obtainable from published approved maintenance schedules. In general it may be assumed that approved TBO is a close enough estimate to achieve TBO.

Complexity is difficult to measure.

Cost of overhaul spares and labor content is precisely what we wish to estimate.

How then can we estimate component costs, retaining simple but truly representative parameters?

One suggestion is to concentrate on just one or two dominant cost producing components, using as parameters their number per system, their TBO, and some sizing or
pricing characteristic. In Table I, for example, numbers of generators are used to represent electrical components, with KVA output as a sizing indicator.

If a large number of observations is available, more components can be added without any danger of reducing the residual degree of freedom significantly and the ability to represent the system costs will have been improved.

3) **Fuselage Length**

Sizing characteristics have already been introduced via the dominant cost producing components, and it would be incorrect to add any further sizing factor if not warranted. If the portions of the system that interconnect the components have little influence on maintenance costs, then aircraft size should not be a parameter of that system. This is true for airconditioning ducts and electrical wiring. However, leaks do occur in hydraulic lines and in fuel tanks; and cables do wear in their passage through grommets and over pulleys and these systems should include "fuselage length" as a variable, the implication being that the longer the connection the greater the probability of a defect.
4) **Number of Seats**

Certain services are supplied on a per seat basis. One is the seat itself (ATA 25) and the others are reading lights (ATA 33), individual cold air louvres (ATA 21), passenger address (ATA 23) and passenger oxygen (ATA 35). Furthermore, the usage given to washrooms and toilets is a function of the number of passengers, so that this parameter should apply to ATA 38. But wherever number of seats is used as a parameter, fuselage length should not be used if an aircraft sizing factor is necessary (to avoid colinearity). The number of seats can itself then serve as an aircraft sizing parameter too, since there is a relationship between size of fuselage and number of seats.

5) **Aircraft Cost** (does not include engines, propellers or rotors)

This parameter is virtually used as a substitute for material costs; and it is presumed that for any system where the size or number of units is a function of the size of the vehicle, then the material costs are proportional to the price of the aircraft. Con-
sequently this variable is not deemed to be applicable to Communications (ATA 23), where the number and the type of HF and VHF units is determined by the route structure, nor to Navigation (ATA 34) for a similar reason.

Furthermore, a strong dependence on this variable is proposed for those systems, viz., Landing Gear (32) and Structures (51-57) where material costs are a dominant factor, and where the systems comprise a major fraction of the airframe.

6) **Number of Engines**

Because of the overpowering influence of engine costs on the total maintenance cost, this is an obvious parameter for systems 71-80. But in addition, Fire Protection (26) and Pneumatic (36) are concentrated around the engines, so that their costs are considered to be related to the number of engines.

7) **Number of Tires**

Tires represent such a heavy cost item that their number is an important independent variable to appear in the Landing Gear regression equation.
8) **Engine, Propeller, Rotor Cost**

In each of their respective systems, this parameter is used for the same reason that Aircraft Cost has been used - as a substitute for material costs.

9) **Hot Air Mass Flow and Fuel Flow**

Turbine engine maintenance costs are unrelated to the manner in which the power is used, i.e., whether it is a turboprop or a turbojet aircraft, but do presumably depend on the amount of power. It was therefore considered desirable to choose parameters that expressed power in terms that needed no additional qualifiers. Hence the use of "hot air mass flow" and "fuel flow", which apply equally to front fan, rear fan, straight jet, bypass and prop jet as a measure of their power. It is not difficult to obtain this information either for existing engines or for "drawing board" engines, since this is a key design specification.

**Engine TBO**

The influence of engine TBO on costs is none too simple. The labor content of overhauls remains reasonably constant regardless of TBO. But material costs may jump sporadically due to the presence of expensive lifed parts, such as turbine
discs. Let us assume a turbine disc has a total time limit of 10,000 hours. When main engine TBO is around the 2000-3000 hour range, it is not too difficult to schedule a disc into an engine in such a way that its time limit is reached coincidentally with the normal overhaul time of the engine. The fourth or fifth overhaul will see a sudden jump in material costs. But gas turbine engines are proving remarkably reliable, operating successfully up to 6000 hours without any need for disassembly. When such an engine is due for its overhaul, what is the best policy? To leave the disc in and cut the next overhaul period down to 4000 hours, or to leave the disc out, install a new disc and trust that opportunities will arise to utilize the 4000 hours of life left? As for the accounting procedure, is the cost of the new disc to be charged as a running maintenance expense, or because of the cost and its long total life, is it to be amortized and not included at all in direct maintenance costs?

Considerations of this nature in engine costs may have more influence over total direct maintenance costs than the costs of some complete systems.

We can be certain that either approved or achieved engine TBO is a parameter that needs to be forced into the 71-80 system regression equation. However, no suggestion can be made
about the treatment of these other factors without some closer study of the policies adopted by the individual airlines. Again, the ATA seems to be the ideal organization to handle this problem.

Operational Characteristics

1) Landings per Hour

This is probably the most important of the operational characteristics. Referring to Table I, wherever a system has specific functioning at takeoff, during descent and landing, so does the system accrue maintenance costs on a per flight basis, and therefore the $/flight hour cost is a function of the landings per hour. Landing Gear (32), the third most costly system, is principally dependent on this parameter, and in fact a number of airlines call up inspections and overhauls of landing gear assemblies on the basis of landings and not on the usual flight hour basis.

Fire Protection (26) generates its costs during preflight checkout; leading and trailing edge flaps plus spoilers (27) come into use during takeoff and landing; refueling (28) is performed on the ground, although not necessarily before every flight hop. Certain parts of the hydraulic system (29) operate on the ground for braking and steering, other parts for flap
and gear retraction and extension, and still other parts for flight controls.

Even the costs of Water and Waste (38) are felt to depend on this parameter, for on short hops these facilities tend not to be used, while on long flights there is considerable usage.

For pressurized aircraft, every flight is equivalent to one pressurization cycle, which is a factor of concern for fuselage structural integrity and consequently both Structures (51-57) and Routine Checks should include this parameter in their cost relationship.

Engines, propellers, rotors, and transmissions are operated under the severest conditions during take-off. Not only are operating limits reached or nearly reached, but the hazards of foreign object damage are greatest then. Thus landings per hour is a critical parameter for these systems too. (Systems 70-80, 61, 84.)

2) Geography and Climate

Dummy variables representing these would account for the corrosive influence on structure of salt-laden atmospheres, the erosive influence on rotor blades and engine compressor blades of sand-laden environments,
the high incidence of icing conditions, and the poor condition of runways. This is likely to be applicable to local airlines only, where the concentration of any one of these factors is high enough to be a determining influence.

Parameters Not Considered Significant

Both the ATA and the Proposed Lockheed formulas base themselves heavily on airframe weight and cruise speed as representative parameters. In analyzing the system by system characteristics, neither of these appears to warrant the importance attached. If airframe weight is meant to be the "sizing" variable for labor content, it is less meaningful than length or area. And as for speed, it is not obvious why this should enter at all, except perhaps to distinguish between subsonic and supersonic, and in this event it is really behaving like a dummy variable, with two possible states -- a subsonic or a supersonic set affiliation.

Allocation of Relevant Parameters

Thumbnail descriptions of each aircraft system are presented in Table I, with manner of operation and prin-
cipal cost elements highlighted. There are a group of basic parameters which are considered to be generally applicable to all systems. The value 2 implies that the parameter may have an influence, and in the control card a 2 specifies a free variable. The value 3 indicates that logical analysis strongly suggests a relationship, and in the control card a 3 forces the parameter into the regression equation. All other parameters which are specifically mentioned should use a 3 on the control card as they are intended to be forced in.

The parameters in Table I emerge from an analysis of systems to be found on current commercial subsonic jets, propjets and helicopter transports. Any attempt to include a vehicle outside this class can be accomplished by diagnosing each of its systems, declaring relevant significant parameters and superimposing this on Table I. Wherever, in an existing system, no parameter exists, a new dummy is created. Wherever no system exists, an additional one must be created.
VII DEMONSTRATION OF TECHNIQUE WITH ACTUAL COSTS

The Available Input Data

The key to the multiple regression technique is an adequate quantity of diversified data. The ideal situation would have been a selection of system costs from among the major trunk and local carriers in this country, with aircraft ranging from the Fokker-Fairchild F27 to the Boeing 797-320B, average trip lengths from 70 to 1700 miles, utilization from 1000 to 4000 hours per year, and reported every year from 1959.

Unfortunately, only four airlines (out of more than 90 polled) record their maintenance costs either by the ATA breakdown, or indeed by any system breakdown which could be related to the ATA system. It is a remarkable fact that most airlines do not know the maintenance costs associated with any given aircraft subsystem. The maintenance accounting procedures are such that a budgetary or actual cost is known for the hydraulics overhaul shop, for example, but no breakdown of costs against hydraulics systems in various aircraft types can be found. Of those that now do, the record keeping is but a recent development. As a result only nine observations of system costs were obtained. Two
of these observations were helicopters, which reduces the observations still further down to seven for some systems. This is not sufficient data to apply the regression technique with any confidence. The resultant available input data is described in Table II, which is coded to protect the identity of one source. It will be noticed that in fact only six observations are complete breakdowns direct from the airlines in the correct ATA 100 form. In the case of two observations the total airframe labor and engine labor costs were given per se, and only material costs were broken down into individual systems. Judgement based on the labor-to-material ratio per system of other airlines, plus the knowledge of the total labor costs gave an assessed value of labor. This plus the actual material cost was used as an input of total costs for the system.

In the case of one observation, the airline had another specific system breakdown which could be correlated to the ATA 100.

Fleet size, utilization, and hours per landing were also supplied by the airlines. All other data pertaining to the aircraft or the airlines was obtained
from a number of sources. Airline and aircraft characteristics are shown in Table III.

Table I presents the minimum desirable group of parameters per system; but because not all have been readily obtainable, this exercise has used a curtailed set, besides which, because of the limited number of observations, not all of these can be used in any one regression run.
Application to Aircraft Subsystems

Using all the data, and the parameter values indicated in Table III, a linear regression model was constructed for each aircraft subsystem as given in Table IV. For example, the estimating equation for System 21 (Air Conditioning) is given by:

Direct Maintenance Cost ($/flight hour)

= .3445
- .0381 x (fleet size)
- .0012 x (utilization - hrs/year)
+ 2.516 x (hrs./landing)
- 8465 x (aircraft cost)
+ .0517 x (aircraft age - months)
+ .0408 x (no. of seats)

Similar linear regression equations were found for each subsystem. Table V shows the actual and the regression estimate for every subsystem observation, and gives the standard error of the model in $/hour.

The regression models of Table V used a dummy variable to differentiate between aircraft and helicopter
systems. By dropping the helicopter data completely, another set of regression equations as given in Table VI was obtained for jet transport aircraft only. As well, the parameter "hours/landing" was inverted to become "landings per hour" since its coefficient could then be related to a system cost per landing or per operation. Table VII gives a comparison of the regression models obtained: first, by using landings per hour with all data; secondly, by deleting the helicopter data while using landings per hour.

In general, these two steps produce a result which has a smaller standard error, and a higher multiple correlation coefficient. In particular, the equation for landing gear using all data showed a positive coefficient with the variable "hours/landing" because the helicopter data showed lower values of cost with much lower parameter values of hours/landings. Without the helicopter data, the trend is positive with landings per hour as would be expected intuitively. Similar objections can be made to various system equation trends with certain parameters. Much more data would be necessary to produce reliable system regression equations for cost estimating.
purposes. The models are shown here simply to demonstrate the technique, and indicate the type of result which might be obtained if ample, reliable data could be gathered.
Application to Total Aircraft Maintenance

An estimate of total direct maintenance cost can be obtained by adding up all subsystems costs. This has the disadvantage of including most of the parameters considered as can be seen from Tables IV and VI. A more accurate and simpler regression equation can generally be constructed by performing the regression using total maintenance costs as the dependent variable.

For example, using jet transport data only, a total cost regression model as given below was obtained.

Total Maintenance Cost ($/hour)

\[
= 54.12 - .735 \times \text{(fleet size)} + 1.375 \times \text{(aircraft age - mos)} - .167 \times \text{(gross weight \times 10}^{-3}\text{)} + .008 \times \text{(engine TBO)} - .081 \times \text{(engine cost \times 10}^{-3}\text{)}
\]

A comparison of the estimating accuracy of the present 1960 ATA maintenance cost formulas, the total systems summation formula, and the above formula is given in Table VIII. Actual data for 1965 (which was not used...
in the regression analysis) was obtained for 6 airline-
aircraft combinations. In this particular comparison,
the total cost regression model is substantially better
than the other two methods, as indicated by the stan-
dard error of estimate. Further study using more ex-
tensive data over a period of years, and studying the
accuracy over a wider sample would be necessary to
validate this type of conclusion.
Discussion of Results

It must be emphasized that the particular results recorded here cannot be considered rigorous in the sense that there is not a sufficient statistical information input. They are presented only to exercise the technique, to ascertain the data requirements to show the problems in using the technique, and to indicate the type of results which can be obtained. Certainly, there are a number of deficiencies in some of the regression models, where the trend of cost with a given parameter is opposite to the expected trend.

The statistical technique of fitting a curve, or straight line in multiple dimensions to a given set of observed data is quite rigorous and well defined. The techniques of constructing the model - selecting parameters, avoiding collinearity, deciding to use logarithmic or other functional representations, etc. - is not rigorous. It depends very much on the intuition, judgment and experience of the analyst. As well as more data, much more experience in using the technique as a tool for maintenance cost estimation is needed. On the basis of these demonstrations, it is a promising tool.
VIII. CONCLUSIONS AND RECOMMENDATIONS

1. A sound maintenance cost estimating relationship which is to be used for extrapolating into the realm of the future conventional fixed wing aircraft must have more factors in it than does the ATA 1960 formula.

   Over and above the parameters which the ATA formula takes into account, such aircraft characteristics as time from type certification, number of seats, major costs producing system components, and number of wheels and brakes can be equally significant.

   Moreover, airline characteristics such as fleet size, utilization, years from the first delivery, seat hours per year per maintenance employee, absent from the ATA formula, should help to explain cost differences between airlines.

   Parameters reflecting the manner in which the vehicle is operated, such as landings per hour, have an influence on hourly costs peculiar to themselves.

2. All of these comments have added validity if the formula is to estimate the costs of a completely new type of vehicle, such as the SST or a VTOL aircraft. In these circumstances, the ATA formula is quite inadequate, and some radical departure from it is warranted.
3. The advantage of a statistical approach in developing a cost formula is that it has the power of eliminating human bias. When final judgment is used, it does not override the statistics, but on the contrary tries to make sense out of the statistics by finding those logical parameters which fit the data.

4. The multiple regression analysis technique manipulates the statistical data and produces the appropriate relationship between the system cost and its relevant parameters. It does so in a well defined step-by-step process that introduces or deletes variables in accordance with prescribed criteria, in order to find that expression which best fits the data set.

However, the technique is as good as the data which are supplied. For reliable estimating, with high confidence levels, it is essential that a determined effort be made to obtain the full cooperation of the airlines. This will require a considerable effort to set up. But once accomplished, the greatest beneficiaries will be the airlines themselves, not only from their direct usage of the formula, but from the by-products that it produces in the way of well classified system costs that are necessary for the data
collection, and so valuable to airline maintenance management.

Once the initial effort is over, the running becomes minimal, both for the airlines, particularly if they are computerized, and for the central processing agency.

5. A central repository of the data, responsible for establishing maintenance and accounting standards, definitions, procedures and administrative practices associated with data collection, is a necessity. This Agency will be required to modify the control cards with each new data input, run the computer program judge the results, conclude the final choice of parameters, and distribute the up-to-date formula to member airlines and other interested bodies. The best choice would be the ATA itself, which in fact already has a committee responsible for recommending a revision of the 1960 formula\(^9\). The ATA has the confidence of the member airlines, and the administrative machinery capable of extending itself to include this new function.

6. A vast amount of historical data already exists within the CAB, the ATA and the airlines themselves
which probably requires processing. As part of the initial setting-up effort, this would be a worthwhile investment, for it might give immediately the reliability the cost formulas obtain by increasing the volume of good input data.

7. The importance of conducting the regression on an individual aircraft system basis cannot be emphasized enough. It enables parameters which have definite system characteristics to bear their full weight where it counts, and not face the danger of being swamped in a gross maintenance cost regression. But above all it makes the task of estimating costs of completely new types much simpler. For the system base is synonymous with the function base, and since the functions of a "drawing board" aircraft and a real aircraft can be compared, so too may the costs be compared.
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BIBLIOGRAPHY


TABLE I

<table>
<thead>
<tr>
<th>CATEGORIZATION FOR APPLICABILITY</th>
<th>PARAMETERS</th>
<th>LOSS</th>
<th>SEATS %</th>
<th>FLEET SIZE</th>
<th>UTILIZATION</th>
<th>FUSELAGE LENGTH</th>
<th>AIRCRAFT AGE</th>
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</table>

**Producing Elements**

- **SPECIAL TRANSMISSION**
  - Main transmission.
  - Subsidiary gearboxes.
  - Lubrication.

- **PROPELLER**
  - blades on rotor
  - propeller or propeller roto
  - pitch control.
  - dampers.
  - rotor blades.

- **PNEMATIC**
  - valves.
  - ducts.

- **CHECKS**
  - Engine EO
  - HOT AIR MASS
  - engines
  - fuel flow or progressive
  - Trouble shooting.
  - valves.
  - repairs.
  - Routine checks.

- **ENGINE POWER**
  - Engines Airframe
  - TBO
  - Thrust reversers
  - indicators.
  - engine vibration,
  - starting system.
  - Overhaul.
  - cowplings.
  - Engine EO

- **WASTE**
  - Motor, Filter, and Timer.
  - Wash basins
  - Water heaters
  - flushing toilets
  - Vater heaters

- **LIGHTS**
  - Beacons
  - Anti-skid systems
  - Dummy for each

- **GEAR**
  - units
  - overhual.
  - Engines
  - R.L.

- **ICE AND PROTECTION**
  - Random. yes no
  - Windshield heat mostly
  - Random yes yes at night
  - Random
  - Windshield deicer mats
  - Instrument shock struts, Pax, reading
  - Deicer mats
  - Climatic spoilers, yes-all

- **HYDRAULIC POWER**
  - Pumps
  - Flaps, plus nose wheel steering, plus L.E. flaps,
  - Brakes
  - Nose wheel steering

- **FLIGHT CONTROLS**
  - Flight controls
  - Rudder, yes Flight controls
  - Ailerons
  - R.E.&A
  - T.E. flaps
  - Flap motors
  - Tank sealing, bladder
  - Tanks, pumps, hydraulic actuators, tanks, Booster pumps, Accumilators,
  - Pedals
  - JAckscrews
  - Dump valves
  - Stability actuators

- **ELEVATOR**
  - Elevator sections
  - L.E.

- **SPOILERS**
  - Spoilers for checkout
  - Spoilers
  - Augmenters

- **FLAPS**
  - Flaps, plus nose wheel steering, plus L.E. flaps,
  - Brakes
  - Nose wheel steering

- **PERFORMANCE**
  - Engines
  - Airframe
  - TBO
  - Pump rating
  - Check engine EO
  - Hot air mass
  - Engines
  - Fuel flow or progressive
  - Trouble shooting.
  - Valves.
  - Repairs.
  - Routine checks.

- **ELECTRICAL POWER**
  - Generators
  - Seats
  - Battery coffee dispensers, refriger., ovens, bottle
  - Soundproofing,
  - carpeting,
  - emergency equip.

- **COMMUNICATION**
  - VHF Transmitters
  - Receivers
  - Hand mikes
  - Headsets

- **HF SYSTEMS**
  - Antennas
  - Transf. rectifiers
  - Control panels
  - Generators

- **AIR CONDITIONING**
  - Air cycle machines
  - Shut-off, Accelerometers and Receivers
  - Airflow control, high
  - Amplifiers
  - Amplifiers

- **AUTOPILOT**
  - Autopilot
  - Autothrottle
  - Flight director
  - Autocaptures

- **NAVIGATION**
  - VOR
  - Inertial nav., Glide
  - Pitot static,
  - Vert.gyro, Loran,
  - Weather radar,
  - system

- **CHECKS**
  - Dummy for each
  - Engine EO
  - HOT AIR MASS
  - engines
  - fuel flow or progressive
  - Trouble shooting.
  - valves.
  - repairs.
  - Routine checks.

- **ENGINE POWER**
  - Engines Airframe
  - TBO
  - Thrust reversers
  - indicators.
  - engine vibration,
  - starting system.
  - Overhaul.
  - cowplings.
  - Engine EO

- **WASTE**
  - Motor, Filter, and Timer.
  - Wash basins
  - Water heaters
  - flushing toilets
  - Vater heaters

- **LIGHTS**
  - Beacons
  - Anti-skid systems
  - Dummy for each

- **GEAR**
  - units
  - overhual.
  - Engines
  - R.L.

- **ICE AND PROTECTION**
  - Random. yes no
  - Windshield heat mostly
  - Random yes yes at night
  - Random
  - Windshield deicer mats
  - Instrument shock struts, Pax, reading
  - Deicer mats
  - Climatic spoilers, yes-all

- **HYDRAULIC POWER**
  - Pumps
  - Flaps, plus nose wheel steering, plus L.E. flaps,
  - Brakes
  - Nose wheel steering

- **FLIGHT CONTROLS**
  - Flight controls
  - Rudder, yes Flight controls
  - Ailerons
  - R.E.&A
  - T.E. flaps
  - Flap motors
  - Tank sealing, bladder
  - Tanks, pumps, hydraulic actuators, tanks, Booster pumps, Accumilators,
  - Pedals
  - JAckscrews
  - Dump valves
  - Stability actuators

- **ELEVATOR**
  - Elevator sections
  - L.E.

- **SPOILERS**
  - Spoilers for checkout
  - Spoilers
  - Augmenters

- **FLAPS**
  - Flaps, plus nose wheel steering, plus L.E. flaps,
  - Brakes
  - Nose wheel steering

- **PERFORMANCE**
  - Engines
  - Airframe
  - TBO
  - Pump rating
  - Check engine EO
  - Hot air mass
  - Engines
  - Fuel flow or progressive
  - Trouble shooting.
  - Valves.
  - Repairs.
  - Routine checks.

- **ELECTRICAL POWER**
  - Generators
  - Seats
  - Battery coffee dispensers, refriger., ovens, bottle
  - Soundproofing,
  - carpeting,
  - emergency equip.

- **COMMUNICATION**
  - VHF Transmitters
  - Receivers
  - Hand mikes
  - Headsets

- **HF SYSTEMS**
  - Antennas
  - Transf. rectifiers
  - Control panels
  - Generators

- **AIR CONDITIONING**
  - Air cycle machines
  - Shut-off, Accelerometers and Receivers
  - Airflow control, high
  - Amplifiers
  - Amplifiers

- **AUTOPILOT**
  - Autopilot
  - Autothrottle
  - Flight director
  - Autocaptures

- **NAVIGATION**
  - VOR
  - Inertial nav., Glide
  - Pitot static,
  - Vert.gyro, Loran,
  - Weather radar,
  - system

- **CHECKS**
  - Dummy for each
  - Engine EO
  - HOT AIR MASS
  - engines
  - fuel flow or progressive
  - Trouble shooting.
  - valves.
  - repairs.
  - Routine checks.

- **ENGINE POWER**
  - Engines Airframe
  - TBO
  - Thrust reversers
  - indicators.
  - engine vibration,
  - starting system.
  - Overhaul.
  - cowplings.
  - Engine EO
**TABLE II - INPUT DATA SOURCES**

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### AIRLINE AND AIRCRAFT CHARACTERISTICS - USED IN REGRESSION ANALYSIS

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<th>FUSELAGE LENGTH FT.</th>
<th>COST (MINUS ENGINES) $x10^4</th>
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<th>SEATS</th>
<th>YRS FROM FIRST DELIVERY</th>
<th>GROSS WEIGHT LB x 10^-3</th>
<th>NUMBER OF TIRES</th>
<th>ENGINE COST $x10^4</th>
<th>ENGINES</th>
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### CHARACTERISTICS OF AIRLINES AND AIRCRAFT NOT USED IN REGRESSION ANALYSIS

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<th>FUSELAGE LENGTH FT.</th>
<th>COST (MINUS ENGINES) $x10^4</th>
<th>AGE OF AIRCRAFT TYPE MONTHS</th>
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<th>YRS FROM FIRST DELIVERY</th>
<th>GROSS WEIGHT LB x 10^-3</th>
<th>NUMBER OF TIRES</th>
<th>ENGINE COST $x10^4</th>
<th>ENGINES</th>
<th>NUMBER OF ENGINES TBO HRS</th>
<th>FUEL FLOW lb/hr</th>
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**TABLE III**
### SYSTEMS AND TOTAL MAINTENANCE COST REGRESSION COEFFICIENTS
(including helicopter data)

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<th>AIRCRAFT AGE</th>
<th>SEATS</th>
<th>YEARS FROM FIRST DELIVERY</th>
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**TOTAL** 118.935  -.708  -.017  +6.916  +.094  +.621  +1.368  -.105  +11.643  -51.343  +3.2331  -.0307

**TABLE IV**
### COMPARISON OF ACTUAL AND FORMULA COSTS

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| Standard error of estimate $/hr. | .0608 | .2505 | .2902 | 1.4952 | 1.1975 | 0.0550 |

**TABLE VA**

All costs $/flight hr.
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**TABLE VB**
COMPARISON OF ACTUAL AND FORMULA COSTS

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### Standard error of Estimate $/hr$

|         | 2.0628   | 13.512   | 11.2808  |

#### TABLE VD

*Notes: 1 - All actuals do not include systems 61,82,83,84 for this column.
2 - If forecast for non-existent systems had been deleted, this would be 127.46. (Systems 22,26,30,35,36,38 are non existent).
3 - If forecast for non-existent systems had been deleted, this would be 140.81.
4 - Not used as input.
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(Jet Transport Data Only - Using Landings/Hr.)

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**TABLE VI**
# TABLE VII
## COMPARISON OF REGRESSION MODELS FOR AIRCRAFT SUBSYSTEMS

Model 1 - All data  
2 - Using landings/hr  
3.- Jet transport data

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### TABLE VIII - TOTAL DIRECT MAINTENANCE COSTS FOR SELECTED AIRLINES

ATA - Study Formula - Actual Reported

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| STANDARD ERROR $/hr | 31.15 | 24.96 | 13.66 |

**Notes:**

1. A value of 3.5 $/man hours has been used. (ATA 1960 uses 3.0 $/hr).

2. Data shown in Air Transport World of May 1965 is given in $ per block hour, and was converted into $ per flight hour with the BLOCK/AIRBORNE ratio.

3. All costs are in $/flight hours.
PART II - MAINTENANCE COST ANALYSIS FOR

HELICOPTER ROTOR AND TRANSMISSION SYSTEMS

C. Pearlman

November 1966
## CONTENTS - PART II

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<td>Application of Potential Limits to Actual Operation</td>
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I. INTRODUCTION

In any study concerned with estimates of the maintenance costs of VTOL aircraft there is bound to be some comparison drawn with the actual costs incurred by commercially operated helicopters, as these are the only example extant of a VTOL machine. This is unfortunate, because the high maintenance costs of these helicopters becomes associated with future VTOL aircraft. Some explanation of these high costs is expected before any case can be made for reasonable cost levels on VTOL aircraft.

Thus, in order to set the stage for further cost studies of VTOL machines, it appeared necessary to examine the reasons why helicopters are expensive machines to maintain.

Part of the answer was given in Reference 1 where it was shown that for those VTOL aircraft subsystems having a counterpart on a Boeing 720B, the ATA formula gave a reasonable estimate of their potential maintenance costs, which were by no means excessive. It remained to investigate those systems which have no counterpart, viz. rotors and transmission, both of which have proven to be costly on maintenance for present helicopters.
There are a number of important factors which must be considered in examining these high costs:

1) Compared to subsonic jet aircraft, helicopters are still relatively in their infancy, and the design level of such systems, from a maintenance standpoint, may be less advanced. A potential for cost reduction therefore would exist.

2) In the very nature of these "special" systems, they are called upon to perform critical functions demanding complex but reliable designs, so that even though the level of design may be the same as on current jets, the greater complexity will lead to higher costs, and consequently no potential for cost reduction would be expected.

3) Obsolescence is a function of calendar time and competitive equipment, while maintenance costs are a function of operating time. Because of the high utilization and large fleet sizes of the 720B operation, it has been possible through standard sampling procedures to achieve high
TBO's and less frequent inspections early in the useful life of these machines. Commercial helicopters, on the other hand, have been operating at about one third to one half of the 720B utilizations, with fleet sizes of one tenth and less. Consequently, even with the most reliable equipment, at the standard rate of sampling, the vehicle is well into its useful calendar life before substantiation has been obtained to enable appreciable increases in TBO, or reduction in maintenance check frequency. A potential for cost reduction does therefore exist, if larger fleet sizes and higher utilization rates are contemplated.

4) Costs are stated in terms of dollars per flight hour, and the helicopter flight hour includes more of the arduous take-off and landing time than does the jet flight hour. One would expect VTOL maintenance costs to be higher.

5) The vibration level on a helicopter is more severe than on a 720B and imposes heavier
maintenance demands. A potential for cost reduction would exist as these levels are reduced by design improvements.

All of these possibilities do in fact exert their influence in varying degrees. How then can one estimate the overall potential maintenance cost?

One method which seemed to bear promise involved the study of two real operations analyzed in a special way. The operations were those of two commercial helicopter airlines in the U.S. Every record of a component removal in the Rotor and Transmission systems was carefully examined against a set of "special rules", and the "justification" for that removal was reassessed. Wherever the removal was not "justified", it was deemed to be avoidable, and the maintenance cost associated with that removal likewise avoidable. The remaining cost was the potential system maintenance cost.
II. PROCEDURE

Special Rules

It was assumed that the helicopters were being operated in a manner comparable to that of 720B's by a major trunk carrier. That is, the components themselves had a high degree of reliability, the vehicles had a high utilization (in the order of 10 hours a day), and the fleet size was large. There are a number of implications associated with such assumptions.

1) The manufacturer who has a large number of his aircraft in commercial service is highly sensitive to the public and operator acceptance of his product. Problem areas evoke speedier and more effective action, and there is strong pressure to allocate the necessary funds for remedial action.

2) High non-recurring engineering costs for modifications can be spread over a large number of aircraft, thereby keeping the overall cost to the operator down, and increasing the likelihood
of having the modification incorporated. The tendency for components to become even more reliable is therefore increased.

3) The rapid accumulation of flight hours enables advantage to be taken of reliable components by reaching high TBO's at a fast rate, and higher achieved TBO's spell lower maintenance costs. Hence the importance of large fleet size and high utilization.

Vehicle Potentials

It was essential to establish if the inherent design limits of the transmission and rotor components dictated the kind of removal rates being experienced. In each case the designers were asked to specify the TBO's considered by them to be feasible from the standpoint of design and wherever there was a problem area to indicate how this might be overcome.

Furthermore, although not directly used in this exercise, information was obtained which has importance
for future design. In many cases it was agreed that the design approach would have been different if maintenance considerations had played a more significant role.

To illustrate the manner in which TBO's were established we may look at the main transmissions. For both vehicles it was agreed that the fatigue limits of the bearings prevented transmission TBO's from proceeding beyond the lifetime of the bearings. Although the designers differed on what the bearing life would be, the same figure of 3000 hours was used for both vehicles so as not to penalize one helicopter.

**Application of Potential Limits to Actual Operation**

The component removal records covering a year's operation were studied, with the "new" TBO's being used as a guide. If, at the end of the reporting period, the component would still have had some hours of useful life before scheduled removal, then the removal and overhaul were considered to be avoidable, and the associated cost was deducted from the actual cost. There is a danger that by this procedure there might be few overhauls in the reporting year and a peak number in the subsequent
year. A check was therefore made to ensure that the total number of overhauls for any component was consistent with the normal scatter that would be planned by a regular airline.

Unusual incidents or practices were reviewed. If the component had a high removal rate at low hours, this was considered to be a design shortcoming, and all associated maintenance costs avoidable. An example was a component on one vehicle which had to be replaced every 120 hours. Another case called for an inspection which involved removing a component at frequent intervals. It is clear that normal maintenance was not intended to include such items.

The term "maintenance convenience" when applied to a component removal is usually a synonym for "no parts in stock". A small operator, although having a higher percentage of spares to installed units, is likely to face this problem more often than the large fleet operator, especially when the component reliabilities are low. Consequently this reason for removal was also treated as avoidable.

-8-
Random events such as an accident or an unrepeated defect were treated as likely to occur in any operation with even the most reliable equipment, and the costs associated with such maintenance were retained. In any case they do not represent a significant cost.

Thus item by item, each recorded removal was judged by the "special rules", and the relevant maintenance costs either deducted from the actual costs or retained accordingly. The new total costs represented the potential achievable system costs if the present helicopters were in large scale service.
III. DATA SOURCES AND TREATMENT

Airline A

The estimated potential maintenance costs of rotor and transmission systems were required in order to substantiate the values of Maintenance Cost Factor for helicopters used in Ref. 1. This meant having all other system costs for the same reporting period. A summary of maintenance costs, classified by the ATA-100 systems, was available for a one year period, so that attention was confined to the following records covering the same period.

1) Time Control Cards. The history of all components listed in the FAA approved Maintenance Schedule is recorded on these cards, which are kept by the maintenance department. The reasons for removal, together with the flight hours since the last overhaul or since new, were obtained from these cards, and helped in the assessment of the manhours that could have been avoided by applying the 'special rules'.

2) Monthly Material Usage Report. This is an IBM run of all the material used and recorded by maintenance
and allocated to one of the ATA-100 systems. It was necessary to correlate this data, kept by the Accounts Department, with the Time Control Cards in order to assess the avoidable material costs, and to extract the relevant costs.

3) **Invoices.** The outside services which were used provided invoices which were matched to the appropriate debits and credits against the Time Control records, and it was ascertained which to extract as avoidable costs. These invoices are kept by the Accounts Department.

No examination was made of routine check worksheets for sources of avoidable costs since in any case scheduled maintenance is recorded under Airframe Inspections and not allocated to systems.

Estimates of the manhour content of all those maintenance items considered avoidable were given by the airline maintenance personnel. This, as a percentage of total assessed labor for the system, enabled the total avoidable system labor costs to be prorated from the Annual Summary.
The approach was similar to that taken with Airline A data, except for the following:

1) Accounting codes had to be cross-referenced with the ATA-100 breakdown.

2) An IBM run of the manhours and the labor costs by Airline B for each month enabled a more accurate assessment of avoidable labor costs.

3) In the monthly IBM run of material usage only costs that could be identified with specific serial numbers were taken, and where possible matched with the maintenance record, and the same action was taken for the manufacturer's invoices.

The costs which are, by virtue of the "Special Rules", avoidable, tend to be on the conservative side because:

a) in case of doubt the actual cost was retained;

b) only when the serial number could be identified were the costs considered; otherwise they were retained.
c) if no accounting record could be found for an item mentioned in a Time Control Card, then no avoidable cost estimate could be attributed to it.

d) Only if labor could be associated with a component removal was account taken. In all other cases, labor cost has been reported under a periodic inspection or a line maintenance code, for which no avoidable costs have been estimated.
IV. RESULTS

The actual costs, the estimated avoidable costs, and the resulting potential maintenance costs for the two airlines covering the period 1/6/64 to 31/5/65 are given in Table I. The potential costs per flying hour, and the potential overhaul costs per flight hour are given in Table II. Actual maintenance costs, actual overhaul costs, and the reduction in overhaul costs due to an increase in TBO alone (as indicated possible by designers) are given in Table III.

The maintenance cost factor was defined in Ref. 1 such that the product of the factor times the estimated maintenance cost of "other" aircraft systems would give the estimated cost for an aircraft with "extra" vertical lift systems such as a rotor and transmission system. The value estimated in that report was 1.3 for advanced helicopters, and the maintenance cost for "other" systems was given as 42.64 $/hour for Airline A and 40.05 $/hour for Airline B.

Based upon the potential maintenance costs given in Table II, the maintenance cost factors are:
Airline A

\[
\text{MCF} = 1.0 + \frac{8.0 + 12.69}{42.64} = 1.49
\]

Airline B

\[
\text{MCF} = 1.0 + \frac{3.97 + 5.71}{40.05} = 1.24
\]

It should be noted that the difference in the cost factors between the two airlines depend on many differing characteristics between the airline route structures, aircraft operation, accounting methods and maintenance management policies. The difference in cost between the two systems is therefore not of itself significant and should not be construed as indicating one airline or aircraft is preferable to the other. The important point is that, even for two such widely differing airline systems, the cost factor originally assumed is justified.
V. CONCLUSIONS

The results show that there is a potential for reducing maintenance costs down to 30-40% of the present costs if we accept the judgement of the designers, and treat the helicopter airline operation as if it were that of a trunk airline.

Furthermore, this study confirms the justification for using a Maintenance Cost Factor of 1.3 for helicopters in the first N. E. Corridor Transportation Study, and allows more confidence in the validity of those results.

There are, consequently, good grounds for believing that if reliability and maintainability were given the importance they deserve at the design stage of a future helicopter, and if adequate flight testing were conducted prior to delivery, then the direct maintenance costs of the vehicle should not exceed 1.3 times the ATA formula estimates. Therefore the D.O.C.'s predicted for future helicopters in Ref. 1 should be achievable.
VI. REFERENCES

**TABLE I. ACTUAL AND POTENTIAL MAINTENANCE COSTS OF HELICOPTER ROTOR AND TRANSMISSION SYSTEMS**

<table>
<thead>
<tr>
<th>Rotor System:</th>
<th>$ Actual Costs (1964-65)</th>
<th>$ Estimated Avoidable Costs</th>
<th>$ Potential Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airline A</td>
<td>24787</td>
<td>34270</td>
<td>23294</td>
</tr>
<tr>
<td>Airline B</td>
<td>13157</td>
<td>22511</td>
<td>28527</td>
</tr>
</tbody>
</table>

Transmission System:

| Airline A     | 28993 | 20696  | 85394           | 22300 | 5746   | 49894           | 6693  | 14950  | 35500           |
| Airline B     | 17048 | 20380  | 53286           | 8898  | 8046   | 28934           | 8150  | 12334  | 24352           |
TABLE II. POTENTIAL MAINTENANCE COST
PER FLIGHT HOUR

<table>
<thead>
<tr>
<th></th>
<th>Total Flt. Hrs.</th>
<th>Labor</th>
<th>Material</th>
<th>Outside</th>
<th>Total</th>
<th>Potential Overhaul Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Airline A</td>
<td>4500</td>
<td>1.39</td>
<td>3.69</td>
<td>2.92</td>
<td>8.00</td>
</tr>
<tr>
<td></td>
<td>Airline B</td>
<td>7862</td>
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<td>1.61</td>
<td>1.62</td>
<td>3.97</td>
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<tr>
<td>Rotor</td>
<td>Labor</td>
<td>1.39</td>
<td>0.74</td>
<td></td>
<td></td>
<td>1.94</td>
</tr>
<tr>
<td></td>
<td>Material</td>
<td>3.69</td>
<td>1.61</td>
<td></td>
<td></td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td>Outside</td>
<td>2.92</td>
<td>1.62</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>8.00</td>
<td>3.97</td>
<td></td>
<td></td>
<td>1.94</td>
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<tr>
<td>Drive</td>
<td>Labor</td>
<td>1.49</td>
<td>1.04</td>
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<td>4.30</td>
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<td></td>
<td>Outside</td>
<td></td>
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<td>Services</td>
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<td>Total</td>
<td>12.69</td>
<td>5.71</td>
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<td></td>
<td>4.30</td>
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</tbody>
</table>

-19-
### TABLE III. **Actual Maintenance Costs**
**Per Flight Hour**

<table>
<thead>
<tr>
<th></th>
<th>Actual Total Cost ($/flt. hr.)</th>
<th>Actual Average Overhaul Cost</th>
<th>Estimated Overhaul Cost due to increased TBO</th>
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</thead>
<tbody>
<tr>
<td><strong>Airline A - Rotor</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Transmission</td>
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<td>3.6</td>
<td>1.94</td>
</tr>
<tr>
<td>Total</td>
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<tr>
<td>Total</td>
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<tr>
<td><strong>Airline B - Rotor</strong></td>
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<td></td>
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<tr>
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<td>3.12</td>
<td>1.32</td>
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<tr>
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</tr>
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<td>Total</td>
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<td>5.42</td>
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