
FUEL CONSUMPTION MODELING OF A TRANSPORT CATEGORY AIRCRAFT USING FLIGHT OPERATIONS QUALITY ASSURANCE DATA: A LITERATURE REVIEW

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ABSTRACT

Fuel is a major cost expense for air carriers. A typical airline spends 10% of its operating budget on the purchase of jet fuel, which even exceeds its expenditures on aircraft acquisitions. Thus, it is imperative that fuel consumption be managed as wisely as possible. The implementation of Flight Operations Quality Assurance (FOQA) programs at airlines may be able to assist in this management effort. The purpose of the study is to examine the literature regarding fuel consumption by air carriers, the literature related to air carrier fuel conservation efforts, and the literature related to the appropriate statistical methodologies to analyze the FOQA-derived data.

INTRODUCTION

Air carriers spend vast sums of money on fuel to operate their fleets of aircraft. This major cost area must be managed as wisely as possible. Extensive research is being conducted by a host of organizations, including government, industry, and academia, but the research is essentially confined to engineering related areas. Little exists in the literature on efforts to examine, on a routine basis, the fuel efficiency of operational air carrier aircraft to determine if improvements are possible.

It is hypothesized that Flight Operations Quality Assurance (FOQA)-derived data can be used in the effort to manage fuel more efficiently through a statistical analysis of the data, specifically using multiple

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regression analysis and modeling. Thus, the purpose of the literature review is to examine the evidence relative to this hypothesis. To accomplish this objective, the author examined literature related to efforts to conserve fuel, FOQA studies, and statistical methodologies used in studies of this nature.

The logical next step following the current study is to apply these statistical tools revealed in the literature to FOQA data and develop a model for fuel consumption for a specific aircraft model.

IMPORTANCE OF THE STUDY

The importance of the current study is based on the consumption of jet fuel by the industry, and the cost savings to the industry and the public that might be realized by using FOQA data to detect higher than normal fuel consumption, which might be caused by airframe or engine abnormalities.

Air Carrier Fuel Consumption

Certified U.S. air carriers consumed more than 13.6 billion gallons of jet fuel in 1997 (domestic operations only), which represents an average increase of 3.5% during each of the previous five years (*Fuel Consumption*, 2001). Based on the following projections, fuel usage will continue to trend upward. The Department of Transportation (DOT) projects that there will be a 3.6% annual increase in passenger enplanements over the next twelve years. The average annual increase of airborne hours for U.S. air carriers is expected to increase by approximately 3.5% during the same period (DOT Federal Aviation Administration [FAA], 1999). These data suggest a substantial growth in the industry and, thus, the potential for even more fuel consumption by air carriers.

Partially offsetting industry growth in terms of fuel consumption are the many improvements that have been made in commercial aircraft fuel efficiency. Greene (1990) points out that air travel tripled between 1970 and 1989, but the growth of fuel use was restrained by a near doubling of efficiency, measured in seat miles per gallon (SMPG). Commercial aircraft delivered 26.2 SMPG in 1970 and improved to 49 SMPG less than twenty years later. Aircraft manufactured in the 1990s achieve approximately 65–80 SMPG.

As a result of the growth in the industry, but tempered by gains in fuel efficiency, fuel usage is expected to increase to more than 19.8 million gallons by 2010 (domestic operations only) (*Total Jet Fuel*, 2001).

According to the Air Transport Association (ATA, 2000), fuel costs is the airline's second largest operating cost category representing approximately 10% of total expenditures. Only labor costs (35%) exceed expenditures for fuel. As might be surmised based on these data, the economics of the air transportation industry are extremely sensitive to fluctuations in fuel usage, as well as fuel cost. As reported by the ATA, jet

fuel prices increased about twenty-cents from March 1999 to December 1999. This increase in the price of fuel resulted in a \$750 million increase in total fuel costs to the industry.

Others concur with Greene that there have been many improvements in the past several years that have resulted in an increase in fuel efficiency, and there will continue to be various gains made in the years ahead. Dobbie and Eran-Tasker (2001) report that a recent survey of airlines determined that a number of different approaches are being taken to minimize fuel consumption and associated emissions. These include continuous descents from altitudes, increased efforts to monitor fuel use to improve information systems, improvement in the effectiveness of aircraft loading process, minimization of fuel tankering, sophisticated route and fuel planning, use of lighter cargo containers, reduced use of paint applications, and many others. Although these approaches may seem minor when considered individually, when taken together and applied system-wide, the resulting savings may be considerable.

RESEARCH METHODOLOGY

The literature review was begun by searching several databases such as ProQuest, the Missouri Education and Research Libraries Information Network (MERLIN), ArticleFirst, FirstSearch, Dissertation Abstracts, aerospace databases, the Federal Register, and others, for relevant articles written in the past several years. The search was limited to more recent articles due to the rapid pace of technological change in the airline industry and the recent development of FOQA technologies. In these databases, several hundred articles were located using keywords of *fuel conservation*, *fuel consumption*, *fuel efficiency*, *fleet performance*, *flight operations* (or *operational*) *quality assurance*, *regression analysis*, and other similar search terms. The abstracts of each of these was read, and approximately 125 abstracts were determined to be relevant to the topic. Full text articles were obtained for 56 articles and all were studied in detail. Of these articles, 14 were deemed valuable and provided the basis for the literature review. Supplementary materials such as DOT fuel usage reports, FAA policy statements, and statistics textbooks were used to round out the literature review.

RESULTS

The literature discussing FOQA, transport aircraft fuel consumption characteristics, aircraft fuel studies, and statistical methodologies appropriate for such an analysis were reviewed.

FOQA

In 1995, the DOT sponsored an aviation safety conference in cooperation with representatives from industry and government. The focus of the conference was the development of additional measures that might be implemented to reverse the trend of increasing number of accidents in the airline industry. One of the significant conclusions of the conference was that the voluntary implementation of FOQA might be the most promising initiative to reduce the number of accidents. Upon the recommendation of the conference attendees, the FAA sponsored a FOQA demonstration project with the following objectives: to develop hands-on experience with FOQA technology in a U.S. environment, document the cost-benefits of voluntary implementation of FOQA programs, and initiate the development of organizational strategies for FOQA information management and use (DOT FAA, 1998). The FAA-funded \$5.5 million demonstration project was begun in July 1995.

Essentially, "FOQA is a program for obtaining and analyzing data recorded in flight to improve flight crew performance, air carrier training programs and operating procedures, air traffic control procedures, airport maintenance and design, and aircraft operations and design" (U.S. General Accounting Office, 1997). FOQA is a voluntary program that involves the routine downloading and systematic analysis of aircraft parameters that were recorded during flight. The recording unit, which receives data from the flight data acquisition unit(s), is either a crash-protected device or a quick access recorder (QAR). The QAR is a device that allows convenient access to the recording medium and typically records more data than crash-protected devices. Three types of analysis can be performed on the data: (a) exceedance detection—this is the continuous comparison of recorded operational data with predefined parameters to detect occurrences that exceed those parameters, (b) data compilation—used to determine the operation and condition of engines and systems, and (c) diagnostics, research, and incident investigation (Holtom, 2000).

Most air carrier aircraft store FOQA data on an optical storage device and then transfer the data to a ground analysis system where it is processed by expert software. Typically, modern digital aircraft capture and store between 200 and 500 parameters per second (U.S. General Accounting Office, 1997), including gauge readings, switch positions, control wheel deflections, control positions, engine performance, hydraulic and electrical system status, and many others.

Along with the benefits of FOQA to flight operations, the data can also have value for the air carrier's maintenance operations. Using data analysis techniques, analysts should be able to detect aerodynamic inefficiencies such as out-of-trim airframe configurations, deterioration of the powerplant, and other deficiencies in the aircraft's systems. Given the

quantity of fuel consumed by commercial aircraft, as discussed earlier, the identification of problems that result in an increase in fuel consumption by FOQA, and subsequent correction of the deficiency, can lead to considerable fuel savings to the airline industry.

Several airlines have implemented voluntary FOQA programs and the benefits are beginning to be documented. Several examples of safety and operational problems for which FOQA provided objective information are cited by the U.S. General Accounting Office (1997). An airline discovered through its FOQA program that the number of exceedances was greater during flight in visual conditions than in instrument conditions. This finding caused the airline's training managers to change the training program to emphasize flight in visual conditions. That is a clear quality and safety benefit provided by FOQA. Another airline's FOQA analysis determined that the incidence of descent-rate exceedances was unusually high at one particular runway at an airport. The cause was determined to be a poorly designed instrument approach procedure that required flight crews to descend steeply during the final approach segment. When these findings were shared with the FAA, the approach was redesigned to correct the problem.

FOQA has provided a number of airlines objective, quantitative information that can be used to evaluate approach procedures that are unusual with respect to rate of descent or excessive maneuvering at low altitude. Airlines have reported that they have used FOQA information to identify and correct a variety of safety problems through changes or renewed emphasis in standard operating procedures, retraining, and the repair of faulty equipment.

The FAA's preliminary estimates of costs versus benefits of FOQA programs are encouraging to FOQA advocates. The annual cost of a U.S. program with 50 aircraft is approximately \$760,000 per year. Savings from reduced expenditures for fuel, engine maintenance, and accident costs are estimated at \$1.65 million per year, resulting in a net annual savings of \$892,000 (U.S. General Accounting Office, 1997).

There were no studies located in the literature that use FOQA data for any purpose. This is not surprising given the relative newness of the technology.

Many airlines plan to integrate the use of FOQA with other quality-based safety and operational programs, such as safety reporting systems and action plans. This will enable FOQA to be one, albeit important, component of an airline's overall quality program.

Fuel Studies

Numerous fuel efficiency or conservation studies were located in the literature, but the vast majority of them are concerned with engineering rather than operational issues. Several articles were located, though, that

have some implications for the current study, mostly in terms of the appropriate statistical analysis. A brief description of these studies follows.

Kauser and Burcham (2001) conducted a study to predict the off-design performance of a generic low-bypass, mixed flow, augmented turbofan with a triple spool layout. Using estimated performance data based on developed by the National Aeronautics and Space Administration (NASA) engine cycle simulation code, the authors compared the data claimed by the manufacturer with the estimated data. The authors' conclusion was that there was significant disagreement between the estimated engine performance data and the manufacturer's specifications across several parameters. The methodologies used for making that determination were not disclosed in the study.

In another study of gas-turbine aircraft engines utilizing NASA engine cycle simulation code, Patnaik, Guptill, Hopkins, and Lavelle (2001) created two analysis approximators to overcome difficulties encountered in engine cycle analysis. The approximators created were based on neural-network and linear-regression methods. Engine optimization typically adjusts a few engine parameters. An engine design optimization problem was then solved using the three analyzers: the original simulation code, the neural-network derived analyzer, and the linear regression derived analyzer. The computation of regression coefficients for the linear regression analysis was performed using ordinary least squares methods. Patnaik et al. concluded that the performance of linear regression and neural network methods as alternate engine analyzers was found to be satisfactory for the analysis and operation optimization of gas turbine aircraft engines.

Other Studies Using Similar Methodologies

A study employing similar methodologies was conducted by Luxhoj, Williams, and Shyur (1997); using regression and neural network modeling approaches to predict inspection profiles for aging aircraft. A primary concern of the authors of this study was multicollinearity (i.e., a condition in which the predictor variables in a regression model are themselves highly correlated) since a high degree of multicollinearity makes the results not generalizable. The interrelationship inherent in the independent variables—flying hours, number of landings, and age of the aircraft—makes some degree of multicollinearity inevitable. Two statistical measures of multicollinearity were discussed—tolerance (TOL) value and variance inflation factor (VIF). TOL is equal to one minus the proportion of a variable's variance that is explained by other predictors. A low TOL value indicates a high degree of collinearity in the model. The VIF is simply the reciprocal of the TOL; thus, a high VIF value suggests a high degree of collinearity. According to the authors, a high TOL (above 0.10) and a low VIF (below 10) usually suggest a relative small degree of

multicollinearity. An attempt was made to remove multicollinearity by removing the linear trend from the observed variables. Both the dependent and independent variables were transformed by replacing their observed values with their natural logarithms. This approach had the desired effect of reducing multicollinearity, but the resulting regression models all had higher coefficients of variation and lower R^2 values than models without such variable transformations. Also of interest in this study was the process utilized to identify the factors influencing the expected number of events. Data grouping strategies were employed to create robust event prediction models that provided event profiles for a representative aircraft. Multiple regression models were developed to determine the best grouping strategy. This study is important in that it introduces methodologies for coping with multicollinearity, which will be of concern in analyzing FOQA data due to the interrelationships of the variables inherent in that data.

A study conducted by Gibbons and McDonald (1999) compared several different approaches to determining the most appropriate functional form of the regression model for a fuel efficiency problem. One of the primary determinants of this issue is the analyst's knowledge of the relationship that exists between the dependent variable and the independent variables. Utilizing knowledge of the signs and ordering of the regression coefficients is accomplished in a deterministic optimization context, where regression coefficients are estimated by minimizing the residual sum of squares subject to certain constraints on the coefficients. The authors assert, based on their scan of the literature, that this approach is widely used in econometric applications, but not so widely used in physical sciences applications.

Studies that generally support the proposed approach were located in the literature in industries other than aviation. Lin, Jovanis, and Yang (1993) conducted a study in the trucking industry where time-dependent logistic regression techniques were applied to assess the safety of motor carrier operations. Of particular interest were the methodologies used to create the models used for comparison, that is, combining numerous covariates. The authors used several tests to assess the significance of variables and models, including a likelihood ratio test for inclusion or exclusion of a variable as a whole and t-statistics for each category of each variable.

Munson and Khoshgoftaar (1990) conducted a study on regression modeling of software quality. The objective of their work was to explore several statistical approaches to the development of predictive models of program quality. The authors explored three kinds of regression models: the combinatorial method; the stepwise regression procedure; and the reduced model. The latter is accomplished by mapping a set of independent variables onto a smaller number of orthogonal dimensions through factor analysis. Beneficially, the process of factor analysis eliminates the problem of multicollinearity, or severe nonorthogonality, discussed earlier in Luxhøj

et al. (1997). Principal components analysis may be used to detect collinearity in the independent variables, and has been found to be useful in measuring the performance of a regression model. This is significant since the coefficient of determination, R^2 , is not a good tool for evaluation of the final regression model. This is due to the fact that R^2 is defined as: $R^2 = SSR/SST$, where SST is the total sum of squares and SSR is the regression sum of squares. Given that SST is constant for all regression models, R^2 can only increase as additional independent variables are added to the equation. Thus, the R^2 statistic does not evaluate the quality of future prediction, only the quality of fit on the sample data. However, the PRESS statistic is based on a systematic examination of the residuals, and the authors assert that the use of the PRESS statistic offers a superior predictive quality.

A study by Irish, Barrett, Malina, and Charbeneau (1998) provides useful information regarding the selection and inclusion of causal variables in a regression model. According to the authors, the first step in selecting causal variables is to identify those variables that have scientific relevance based on hypotheses about the controlling processes. The second step in the selection process is to use regression analysis to choose those variables that have statistical relevance to the process. This is accomplished through hypothesis tests that determine whether a coefficient of a model variable is statistically different from zero. The authors state,

All relevant explanatory variables exhibit the following three traits: 1.) Some underlying scientific theory explains the response of the dependent variable to a change in the explanatory variable, 2.) The explanatory variable, when included with all of the other explanatory variables, must individually add some new information to the model (i.e., the variable cannot be perfectly collinear with any other variable), 3.) The explanatory variable is known with certainty or at least capable of being measured with a high degree of accuracy (p. 988).

The method of selecting variables to include in the regression model is strictly subjective and left up to the discretion of the analyst. Multicollinearity affects the data, so the modeler must understand that higher values will result for the variance of the estimated coefficients, causing the standard error of the regression to be higher than it would otherwise and, therefore, the t -ratio to be smaller. The predictive performance is not affected by multicollinearity of the data, but the individual affects of each explanatory variable on the dependent variable will be obscured by the phenomenon.

Irish et al. (1998) used a three-step approach to search for the most parsimonious suitable model. The first step was an overfit of the model; that is, the regression equation is formulated using every known causal variable, and each coefficient is evaluated using two tests—statistical

relevance and scientific relevance. Variables that fail both tests are discarded. The regression equation is revised and the new coefficients are examined for relevance. This procedure was repeated until all variables that failed both tests were eliminated. The second step was to make individual judgments about variables that failed only one of the two tests. The final step of the process involved reconsidering the discarded variables, since it was possible for a variable that was previously discarded to become relevant in the new model formulation having fewer variables.

CONCLUSION

This literature review revealed several important facts. First, studies utilizing FOQA are absent from the literature. This should not be taken to indicate the lack of value FOQA data and analysis might have in studies of the nature contemplated in this work; rather, it is indicative of the newness of the technology. In fact, it can be assumed that air carrier personnel are working on analyses of this kind. Given the potential of analysis of safety and operational conditions using FOQA data, and the complexity and extensiveness of the data, there is tremendous opportunity for research in this field by researchers and analysts with interest and expertise.

Second, it is clear that fuel conservation is of major concern to the industry. Studies by IATA and ICAO are evidence that much consideration is being given to various approaches to managing fuel efficiency more carefully. According to ICAO, even seemingly insignificant improvements can amount to substantial savings on a global scale.

Third, regression modeling appears to be the appropriate statistical approach for a study of air carrier fuel consumption using FOQA data and statistical analysis. Several studies in related and unrelated fields demonstrate the use of regression analysis for modeling purposes. These studies use various methods for selection of causal variables and testing procedures to determine statistical relevance. Techniques for coping or compensating for multicollinearity are provided, and extensive discussion of the development of the regression model is presented. It is anticipated that these techniques and methods, as appropriate, can be used in the development of a fuel consumption model using FOQA data for an air carrier aircraft.

Fourth, FOQA data can be compared to manufacturer's specifications at various flight conditions to determine the accuracy of the manufacturer's models. In addition, the development of fuel efficiency models independent of those established by the manufacturer is possible using these methods.

Finally, it should be noted that many airlines have extensive quality programs in place for safety and operations. Any improvements resulting from FOQA data-driven fuel consumption models should be incorporated into the overall quality system.

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