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Economic Analysis of the Effect of Aviation Weather Forecasts on Fuel Expenditures of Qantas Airways Limited

K. A. Anaman, S. C. Lellyett, G. S. Avsar

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VICTORIA UNIVERSITY OF TECHNOLOGY
P O BOX 14428
MELBOURNE CITY MC VIC 8001
AUSTRALIA

TELEPHONE (03) 9688 4492
FACSIMILE (03) 9688 4050

Footscray Campus

Economic Analysis of the Effect of Aviation Weather Forecasts on Fuel Expenditures of Qantas Airways Limited.

by

K. A. Anaman*

S. C. Lellyett**

G. S. Avsar***

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* Graduate School of the Environment and Climatic Impacts Centre, Macquarie University, Sydney, Australia.

** Australian Bureau of Meteorology, New South Wales Regional Office, Sydney, Australia.

*** Department of Computer and Math Sciences, Victoria University of Technology, Melbourne, Australia

Abstract

The effect of weather forecasts on fuel expenditures of Qantas Airways Limited was undertaken by estimating a function with fuel expenditures as dependent variable. Independent variables were price of aviation fuel, airline output, capitalisation, fuel policy and accuracy of upper atmosphere wind forecasts. Fuel price and output had positive impact on fuel expenditures. Increased capitalisation led to reduced fuel expenditures. Abandonment of *mandatory requirement* for pilots to carry *alternate* fuel, in favour of carrying *such extra fuel* based on terminal aerodrome forecasts, saved about 41 million Australian dollars annually. The effect of winds forecasts on fuel expenditures was not established.

Keywords: benefits of weather services, cost functions, meteorological services, time-series economic analysis, cost-benefit analysis

I. Introduction

Improving the quality of weather forecasts supplied to airlines can lead to reduced fuel loads, number of diversions and holding time, and increased safety. Fahey (1993) estimated that cost saving achievable from carrying less fuel as a result of improved weather information could be equivalent to up to 30% of total fuel burned for some international flights especially for short sectors or routes. The reduction in the number of diversions due to improved aviation weather forecasts also results in direct airline benefits such as reduced crew wages and maintenance expenses; and related indirect benefits such as reduced passenger inconvenience and lost business and leisure time.

There has been a relatively large volume of economic studies published on the supply and demand for air travel (e.g. Alperovich and Machnes, 1994; Kirby, 1986; White, 1979; Strazheim, 1978; Sarndal and Statton, 1975). These studies also include those dealing directly with effects of safety-related issues (e.g. Rose, 1992; Barnett and Higgins, 1989; Chalk, 1987). The aviation industry is regarded as weather-sensitive. Weather information is very important to airlines for a number of reasons described earlier and it is also legally prescribed for most civil flights in all countries. It is surprising that detailed economic studies on the evaluation of the economic benefits of aviation weather forecasts reported in the literature are very limited and quantitative economic studies on this subject are virtually non-existent. The few published studies involve very simple underlying economic models (e.g. Beckwith, 1989; Robinson, 1989; Fairbanks *et al*, 1993; McFarlane and Shorthose, 1994).

Murphy (1994) discussed several current research issues dealing with the methodological and practical problems in establishing the economic value of weather forecasts and information. These included the need to apply alternative methods for estimating the value of weather forecasts at the firm and market level. One such method not explored is the use of *cost function analysis* to directly estimate the value of weather forecasts through the reduction of operating costs of business firms which use weather services (Anaman *et al.*, 1995). We used a cost function analytic approach to derive the impact of weather forecasts on fuel expenditures of an international airline. Specifically a total fuel expenditures function for Qantas Airways Limited was derived using econometric procedures. The function was used to determine the effect of policy change involving terminal aerodrome forecasts to decide to carry additional or *alternate* fuel. The effect of the quality of upper atmosphere wind forecasts on total fuel expenditures of the airline was also determined based on yearly aggregate data from 1971/72 to 1993/94.

Qantas uses several aviation weather services provided by the Australian Bureau of Meteorology and other services available through the Bureau of Meteorology via international conventions and agreements administered by the World Meteorological Organisation. In 1993/94, the company paid about six million Australian dollars (A$) to the Bureau of Meteorology through the Civil Aviation Authority for the use of aviation services (Leigh, 1995). Apart from the recognised safety value of aviation weather services which are legally prescribed in Australia and other countries, Qantas Airways Limited is one of a few international airlines which have undertaken extensive reappraisal of information contained in aviation weather forecasts to minimise operating costs without sacrificing any aspects of safety. The airline has a first class safety record.

In late 1985, it decided to drop the mandatory requirement for its pilots to carry *alternate* or additional fuel for the possibility of adverse weather on its international flights. Rather the carrying of such an additional level of fuel to the total fuel load of an aircraft was linked to the information from aviation weather forecasts and the availability of aerodromes for diversions when required. *The alternate fuel load is additional to the basic minimum fuel load needed for a flight plus other required fuel allowances such as air traffic control holding fuel, contingency fuel, fixed and variable fuel reserves (Qantas Airways Limited, 1993).* While anecdotal evidence suggests that the airline could be saving significant amounts of money from its fuel policy, rigorous economic analysis to estimate the extent of direct economic benefits would be useful to the airline and especially to its weather information provider, the Bureau of Meteorology, in the allocation of increasingly scarce manpower and financial resources to its activities which cover all sectors of the Australian economy including aviation and the closely-related tourism sector and also international obligations through the World Meteorological Organisation.

The objective of this study was to analyse the effect of the use of aviation weather forecasts on the fuel consumption expenditures of Qantas Airways Limited using an econometric model. A specific objective was to determine whether the alternate fuel policy instituted by Qantas Airways Limited in late 1985 with regards to the use of terminal aerodrome forecasts had been economically beneficial to the airline. This paper is organised as follows: firstly a background review is presented on various types of aviation weather forecasts and information used by international airlines. Secondly, the methods and procedures used for this study are discussed with emphasis on the economic theoretical framework and empirical analysis and data sources. The results are then presented followed by conclusions, acknowledgments and the references.

II. Background Review of Aviation Weather Services

Provision of basic meteorological information is a major component of the operation of civil aviation in any country. This is because safety-related requirements are crucial to the aviation industry. Meteorological information is needed in all phases of planning and operation of flights. However as noted by Fairbanks *et al.* (1993), accurate information on low-level hazards (near the ground) is especially important because loss of control of the aircraft can lead to extensive damage and human casualties in the aircraft and in the area around the flight path. Meteorological hazards important to the aviation industry include low-level windshear (where windspeeds change by large amounts in a local area near to the ground), microbursts, icing, mountain lee waves (atmospheric turbulence near mountain terrains), turbulence, fogs, low visibility and thunderstorms (Australian Bureau of Meteorology, 1981). Forecast information on these hazards are provided to airlines based on institutional arrangements. The main forecasts issued include terminal aerodrome forecasts (TAFs), trend type forecasts (TTFs), significant weather charts and upper atmosphere wind and temperature forecasts. These forecasts are discussed below:

Terminal aerodrome forecasts (TAFs)

Terminal aerodrome forecasts are predictions of the meteorological conditions over a specified period of time, usually ranging between 6 and 24 hours, for the airspace within an eight kilometre radius of the aerodrome or airport (Bureau of Meteorology, 1981;

Shanahan, 1973). They normally contain predictions of wind velocity, visibility, cloud height and type, plus any weather events such as rain, thunderstorms, duststorms, fog and any other meteorological occurrences which may affect the safe operations of aircraft in the vicinity of the aerodrome, especially take-offs and landings. TAFs for the major international airports in Australia are issued by the Bureau of Meteorology every six hours and with a validity period of 24 hours.

Airlines must as a legal requirement obtain these forecasts prior to take-off and use them in planning the amount of fuel to be uplifted. If adverse conditions within certain specific criteria are predicted in the TAF applying for the destination aerodrome, uplift of extra fuel will be legally required for either holding (that is enough fuel to circle the destination airport for a prescribed period) or for flight to an alternative airport (called 'alternate fuel') predetermined before take-off. In some extreme cases, weather conditions forecast in the TAF may justify closing an aerodrome completely to all air traffic. TAFs are also used by air traffic controllers to determine the runway configurations and the maximum number of landings and takeoffs possible in a given weather situation. TAF predictions and verification data for each six-hourly period are classified into four groups in a contingency table based on the extent of *additional* fuel required to deal with adverse weather conditions around the destination aerodrome at the time of landing. The four groups are described as follows (also refer to Figure 1).

Criterion 1: Expected weather conditions around the destination port would be favourable for normal landing. *No additional or alternate* fuel for weather-related adverse events would be required except the 30 minutes contingency fuel reserve (**NO ALTERNATE OR NO ALT CONDITION**).

Criterion 2: Expected weather conditions at the destination port are likely to be adverse for a long period and safe landing may not be possible. Diversion to an alternative aerodrome should be planned for. *Alternate* fuel equivalent to 60 minutes flying time in addition to the 30 minutes flying time contingency fuel reserve must be added to the total fuel load before departure. This is called the **ALTERNATE OR ALT CONDITION**.

Criterion 3: Expected weather conditions at the destination port are likely to involve *intermittent* occurrences of adverse events likely to last for short periods of less than 30 minutes. Hence 30 minutes of flying time fuel may be added to the total fuel load before departure. In practice, the 30 minutes flying time contingency fuel reserve is the operational requirement. This is called **INTERMITTENT OR INTER CONDITION**.

Criterion 4: Expected weather conditions at the destination port are likely to involve *temporary* occurrences of adverse events likely to last from 30 to 60 minutes duration and not cover more than half the specified period. Sixty minutes of additional flying time fuel in addition to the 30 minutes contingency reserve fuel should be added to the total fuel load before departure. This is the **TEMPORARY OR TEMPO CONDITION**.

TAFs are also used in-flight together with Trend Type Forecasts (TTFs, discussed in the next section). There is a critical stage of each flight called 'Decision Point All engines operating' (DPA) at which the flight crew must decide whether to proceed to the originally intended destination, or to divert to an en-route alternate port. The most current TAFs and TTFs available for both ports and amount of remaining fuel are central to making this decision. For Qantas only under certain specific criteria is alternate fuel *legally* required, at other times it is at the pilot's (captain's) discretion (Qantas Airways Limited, 1993). This flexibility in deciding to carry alternate fuel is not used by all international carriers. The policies of many airlines flying to Australia, for example, require their pilots to uplift alternate fuel even when TAFs do not legally require it. Qantas followed this policy until 1985 when it changed its fuel policy to require pilots to carry alternate fuel only when it is a legal requirement of the TAF or inclement weather conditions are forecast (J. Gilchrist, personal written communication, July 1995). Since alternate fuel will only be uplifted if it is a legal requirement, or inclement conditions are forecast; costs of diversions will be less if TAFs are more accurate since diversion conditions tend to be over-forecast. When there is no legal requirement for uplifting alternate fuel, additional freight, mail or passengers may be included in the aircraft generating extra revenues for the airline.

Figure 1: TAF Six-Hourly Weather Forecast Contingency Table, Corresponding Management Decision and Errors With Regards to Carrying of Extra Fuel.

BUREAU OF METEOROLOGY FORECASTS

ACTUAL WEATHER OBSERVED	NO ALT	ALT	INTER	TEMPO
NO ALT	Correct Decision	60 minutes unnecessary fuel carried	No unnecessary fuel carried	60 minutes of unnecessary fuel carried
ALT	Diversion mandatory since critical alt fuel is not carried. Pilot has no choice.	Correct Decision	Diversion mandatory since critical alt fuel is not carried. Pilot has no choice.	No unnecessary fuel carried
INTER	No unnecessary fuel carried	60 minutes unnecessary fuel carried	Correct Decision	60 minutes of unnecessary fuel carried
TEMPO	Diversion probable because tempo fuel is not carried	Enough fuel carried to attempt landing if necessary	Diversion probable because tempo fuel is not carried	Correct Decision

Trend Type Forecasts

Trend Type Forecasts (TTFs) are similar to TAFs in their structure and the information they provide, however they are supposed to be in some sense updates on the TAF valid only for the immediate next three hours from the time of issue. In a dynamic and rapidly changing weather situation it may be exceedingly difficult to predict with high resolution and accuracy meteorological conditions into the future, thus it is possible that the TAF suffers a degradation in accuracy over its period of validity. In such a situation the TTF supersedes and overrides the TAF. Planning for domestic flights within Australia are based on a combination of TTF and TAF, with more emphasis given to the TTF for flights estimated to be of less than three hours duration. However, in the case of international flights the TAF is used for flight planning prior to take-off, except for very short routes such as Sydney to Auckland, New Zealand where the TTF would also play a significant role in planning. It is standard procedure en-route on international flights that when approaching the DPA, the flight crew obtain copies of the most current TAF and TTF for the proposed and alternate destinations. Usually at this point flights are within three hours of their intended destinations, hence the TTF would be commonly used to make the decision to divert or not at the DPA. Verification statistics for TTFs were not available.

Upper atmosphere wind and temperature forecasts

Flight crew obtain prior to take-off and carry during flight predicted en-route winds and temperatures. This is a standard procedure for all Qantas international flights. Proper use of this information in the planning stage, as well as making in-flight adjustments can lead to substantial fuel savings. Jet aircraft are susceptible to strong winds that are associated with jet streams in the higher levels of the troposphere. Flying time may decrease or increase depending on whether the effect is a tail wind or a head wind. The upper wind forecasts are particularly significant in situations where there are jet stream winds, greater than 100 knots, and in sharp troughs where the wind direction can change over a relatively short distance by up to 180 degrees. The wind component of the upper atmosphere forecasts can therefore be used to avoid headwinds and make best use of tail winds to reduce fuel consumption and flying time (Australian Bureau of Meteorology, 1981). Temperatures also have some impact on fuel consumption since burning of fuel to provide propulsion used on commercial jet aircraft is a thermodynamic process that involves the surrounding air. However effects of changes in temperatures on fuel consumption is considered to be minor compared to that of winds (G. Rennie, personal communication, Aug. 1995).

Commercial aircraft generally cruise (the majority of the flight time) at high altitude in the upper troposphere. Most of the forecasts for this part of the atmosphere are derived from computer model output, which is generally available at several standard levels. The closest of these levels on the majority of occasions is the pressure level of 250- hecto Pascals (250 hPa) - this is quite significant in terms of the wind component of the forecast given that the jet stream, bands of narrow but very high winds commonly ranging from 100 to 160 knots, is often located at this altitude.

In this study we hypothesised that aircraft fuel consumption was linked to the accuracy of upper wind forecasts. As a representation of the accuracy of these forecasts we used the root mean squared errors of the forecast wind velocity as compared to radiosonde observations. The forecasts deal with the expected speed of winds over several sectors of the globe. These forecasts are issued 12, 18, 24 and 30 hours ahead and are available at zero and 1200 hour Universal Coordinated Time (UTC). Currently they are produced under the World Area Forecast Service (WAFS) operated by the United States National Weather Service and the United Kingdom Meteorological Office for all sectors of the globe flown by international carriers (African, Asian, North American, South American, European and Australasian sectors). In the Australasian sector, from 1972 to 1988, the Australian Bureau of Meteorology produced upper atmosphere wind and temperature forecasts for Qantas Airways Limited. From the beginning of the 1988/89 financial year, Qantas switched to using the WAFS forecasts for its routes in all sectors of the globe including the Australasian sector. Verification data for these forecasts are kept by the Australian Bureau of Meteorology from 1972 to 1988 specifically for the Australasian sector. Verification data since 1988 are available for all sectors of the globe from the United States Weather Service. These verification data collated from 1972 to 1994 were used for the construction of fuel expenditures econometric model. Other types of aviation weather services include the Code Grey warnings.

III. Methodology and Data

(i) Specification of Models

Based on the assumption that a firm minimises the costs of producing any given level of output, economic theory suggests that the cost function of the firm can be derived from its underlying production function. Therefore without knowing the exact nature of the production function, an appropriate cost function can be assumed and estimated for policy analysis if the assumption of cost minimisation is reasonable for a business firm. For example, the long run total costs of an airline company is determined by factors such as output, technology, prices of factors of production (capital and labour) and quality of meteorological information service supplied to the firm (O'Connor, 1993, pp. 62-65). Quality of meteorological information may improve over time thus reducing the operating costs of an airline especially its fuel expenditures. A flexible form of cost function can allow the establishment of the effect of the quality of meteorological information on the total cost of a business firm such as an airline company. The transcendental logarithmic cost function is a common method for estimating airline cost functions. Statistical estimation of translog cost functions is discussed by Berndt (1991).

Because of high aggregation of total costs data, it was difficult to establish a relationship between the total costs and weather forecasts. A single variable, total output measured in available tonne-kilometres, explained 99.9% of the variation in the total cost of the airline. Since aviation weather information supplied to airlines is partly used for deciding the amount of fuel to load on the plane and for basic safety considerations which in turn are related to fuel policy, a model based on total fuel expenditures function was the preferred means to analyse the effects of aviation weather forecasts on airline operating costs. Another justification for the use of fuel expenditures function to isolate the effects of aviation weather forecasts is that due to the nature of airline operations, there is very little scope for substitution between fuel and other inputs such as labour. Airlines must carry a certain minimum amount of fuel for all flights. However there is some modest scope for reducing fuel expenditures based on the quality of weather forecasts through avoiding carrying of *alternate* fuel described earlier.

This study involved the estimation of the long run total fuel expenditures function for Qantas Airways Limited based on data from 1971/72 to 1993/94, a total of 23 years. The total fuel expenditures function was estimated using multiple regression procedures from the Statistical Analysis System (SAS) statistical package (SAS, 1994). The total fuel expenditures of the company was the dependent variable of the model. The independent variables were the wholesale price of aviation turbine fuel, output of the airline measured by available tonne-kilometres, capitalisation of the airline (measured by the annual depreciation of aircraft, simulators and spare parts), fuel policy of the airline dealing with the use of TAFs and the quality indices of several aviation weather forecasts. Since effects of changes in temperatures on fuel consumption were considered to be minor compared to those of winds, only the winds components of the upper atmosphere forecasts were used in the analysis. All costs were deflated by relevant Australian consumer price index (CPI) and converted to average 1993/94 prices (average 1993/94 CPI was assigned the base index of 100). Two types of models were initially estimated - the *translog fuel expenditures function* and *loglinear function*. The loglinear model is specified as follows in Equation 1:

$$\begin{aligned}&\textbf{LOG FUELCOST}_t = \textbf{A}_0 + \textbf{A}_1 \textbf{ TAF FPOLICY} + \textbf{A}_2 \textbf{ LOG OUTPUT}_t \\ &+ \textbf{A}_3 \textbf{ LOG PRICEFUEL}_t + \textbf{A}_4 \textbf{ LOG PCAPITAL}_t + \textbf{A}_5 \textbf{ LOG TAFQUALITY}_t \\ &+ \textbf{A}_6 \textbf{ LOG UPPER WINDQUALITY}_t + \textbf{U}_t \qquad \textbf{(EQUATION 1)}\end{aligned}$$

where A_t were the values of coefficients and U_t was the error term;

FUELCOST was the annual deflated (using Australian consumer price index) of total fuel expenditures for Qantas Airways Limited based on average 1993/94 economic conditions expressed in million Australian dollars (A$);

TAF FPOLICY was a dummy variable used to specify the policy change that occurred in late 1985 (in the middle of the 1985/86 financial year) when Qantas abandoned its *mandatory policy* of requiring pilots to carry *alternate* or additional 60 minutes flying time fuel for the possibility of severe weather events at destination ports. Because of the initial cautious implementation of such fuel policy, it was expected that full implementation of policy took place after about six months, during the 1986/87 financial year. Hence a value of 1 was therefore used for the 1986/87 financial year and beyond (after the change) and a value of 0 for years before 1986/87.

OUTPUT was the total annual output of the airline measured either in available tonne-kilometres (ATK). ATK measures the available capacity of the airline and is the product of the total distance travelled and the available space on the planes for carrying passengers, freight and mail. Tonne-kilometres performed (TKP) is an alternative measure of output and measures sales performance. TKP is equivalent to ATK multiplied by the revenue load factor, that is the proportion of available space that is used for actually carrying passengers, freight and mail (traffic) during the year. Because fuel is used to carry planes whether it was full or empty, ATK was preferred to TKP as a measure of output. The initial regression analysis conducted with both ATK and TKP confirmed our choice of output variable. It was expected that fuel consumption of the company would increase with output.

PRICEFUEL was the average of the wholesale price for aviation (jet) fuel at Sydney deflated by the Australian consumer price index (CPI) and U.S. dollar denominated wholesale fuel prices converted to Australian dollars by relevant exchange rates and also deflated by the Australian CPI. This was expressed in Australian cents per litre. It was expected that total fuel expenditures would rise with increased prices of aviation fuel.

PCAPITAL was the annual depreciation of aircraft, engines and spare parts in millions of Australian dollars deflated by Australian CPI. The variable measured the capitalisation of the airline with higher real value of capitalisation implying the acquisition of newer more fuel-efficient planes and the retirement of older planes. As such increased capitalisation was expected to lead to reduced fuel consumption.

TAFQUALITY was average annual accuracy of terminal aerodrome forecasts for the four major ports (Sydney, Melbourne, Brisbane and Perth). A relevant accuracy variable was the proportion of all forecasts correctly predicted (fraction correct) for the major Australian ports. Other types of forecast verification quality indices are reported by Wilks (1995, Chapter 7). Since Qantas' flights always carried alternate fuel before late 1985, the relevant **TAFQUALITY** was set to zero for the 1984/85 financial year and earlier years indicating that the variable had no effect on fuel consumption. Actual TAF accuracy figures were used for years after the 1984/85 financial year. Hence **TAFQUALITY** virtually became a dummy variable similar to **TAF FPOLICY.**

UPPER WINDQUALITY was annual average accuracy of 24-hours upper wind speed and direction forecasts. *Because only the Australasian sector had the complete set of verification data for the 1971/72 to 1993/94 period, the quality index established for the variable was based on data for this sector only.* However data from 1988/89 to 1993/94 indicated that very high correlations existed among the different sectors of the globe for the upper atmosphere wind quality indices justifying use of the data set available for the Australasian sector from 1972/72 to 1993/94 as a proxy for all sectors of the globe flown by Qantas over that period. The quality index used was based on the average root mean square error at 250 hPa pressure which closely resembled the pressure at the cruising altitude of jet planes used by Qantas Airways Limited. It was also the 250 hPa wind (and temperature) forecasts that are routinely provided to international flight crew based on Qantas' policy (personal communication, Graham Rennie, July 1995).

Up to 1978/79, Qantas used its own en-route upper atmosphere wind and temperature forecasts for its flight operations world wide. From 1979/80 it started using upper atmosphere wind and temperature forecasts available from Australian Bureau of Meteorology because of its needs for improved weather forecasts for the Australasian sector only. During this period the airline relied on the United States Weather Service for its forecasts for the other sectors of the globe other than the Australasian sector (Graham Rennie, personal communication, September 1995). The quality indices of the upper wind forecasts used by Qantas from the 1971/72 to 1978/79 period were not archived. Hence based on the perceived better wind forecasts available from the Bureau of Meteorology, the upper atmosphere wind forecasts used by Qantas from the 1971/72 to 1978/79 period were regarded as unimproved information *vis a vis* those obtainable from the Bureau. Therefore the quality of the en-route upper wind forecasts in the 1971/72 to 1978/79 period was assigned a value equal to the average of the worst yearly root mean squared error (RMSE) results achieved by the Bureau in the 1971/72 to 1978/79 period. From 1979/80 onwards, when Qantas used forecasts from Bureau's sources, the quality of wind forecasts was defined as the difference between RMSE for the particular year recorded by the Bureau and the assumed average RMSE of the unimproved information (i.e. 1971/72 to 1978/79 period).

Estimation of long run translog fuel expenditures function (Equation 1) using ordinary least squares (OLS) procedure generated implausible coefficients for the variables. The model was therefore rejected in favour of its log-linear model version. This involved reducing the translog model by removal of variables containing cross product terms. Because of high correlation between **TAF FPOLICY** and **LOG TAFQUALITY**, the model was further reduced by one variable by dropping **LOG TAFQUALITY** to avoid the problem of multicollinearity. This loglinear model version is specified in Equation 4. The fuel policy change reduction factor is $((e^{A0})/(e^{A0+A1})) - 1$ or $((1/e^{A1})-1)$. It measures the proportional reduction of fuel consumption as a result of the policy change related to TAFs to decide the amount of fuel to be uplifted. The annual fuel expenditures saving as a result of TAF policy change is this reduction factor multiplied by the total fuel consumption for the year concerned (Halvorsen and Palmquist, 1980).

(ii) Unit Roots and Co-integration Tests

OLS estimation of the long run fuel expenditures function is only valid under stringent conditions and assumptions with regards to the properties of the error term. An autoregressive time series model can be represented as below in Equation 2:

$$\mathbf{Z_t = hZ_{t-1} + U_t} \qquad \textbf{(EQUATION 2)}$$

where Z is an economic variable, h is a real number and U_t is an error term normally distributed with zero mean and constant variance. If the absolute value of h is less than 1 then Z_t converges to a stationary series as t approaches infinity; if h is equal to 1 then there is a single unit root and Z_t is non-stationary; and if the absolute value of h is greater than 1 then the series is explosive. OLS estimation of a time series model results in biased and inconsistent estimates if the variables are not stationary. In order to derive meaningful estimates of the parameters of a time-series model, a key condition is that residuals of the estimating equations must be stationary. This condition will be achieved if all the variables in the model are stationary i.e. integrated of order I(0). Alternatively if some of the variables are integrated of the order I(1), consistent estimates of the model can still be achieved if the non-stationary variables are integrated of the same order and are cointegrated. The first step involves the determination of the order of integration of the variables in a model. The most common unit-root test is the Augmented Dickey-Fuller (ADF) test. In this study, each variable included in the long run fuel expenditures model, which is specified in Equation 4, was tested for stationarity using the model described by Equation 3 estimated by OLS. This model is as follows:

$$Z_t = h_0 + h_1 Z_{t-1} + h_2 \Delta Z_{t-1} + U_t \qquad \text{(EQUATION 3)}$$

where Δ denotes the lagged first difference of the variable and h_1 and h_2 are the coefficients to be estimated. All the variables in long run fuel expenditures function (Equation 4) were found to be non-stationary making the OLS estimates meaningless. Therefore an investigation was conducted on whether a linear combination of these I(1) variables were stationary (i.e. co-integrated) using a procedure by Johansen (1988). The procedure was based on testing whether estimated residuals of the model contain a unit root. This test produces log likelihood ratio tests which can be used to derive improved estimates of the long run fuel expenditures function denoted in Equation 4 below.

$$\text{LOG FUELCOST}_t = A_0 + A_1 \text{ TAF FPOLICY} + A_2 \text{ LOG OUTPUT}_t + A_3 \text{ LOG PRICEFUEL}_t + A_4 \text{ LOG PCAPITAL}_t + A_5 \text{ LOG UPPER WINDQUALITY}_t + U_t \qquad \text{(EQUATION 4)}$$

In the short run period, there may be a disequilibrium and the error term (U_t) from Equation 4 can be assumed to be an equilibrium error. This equilibrium error is used to link the short run behaviour of fuel expenditures to its long run value. This approach to modelling time-series events is called Error Correction Mechanism (ECM). The ECM model used in the study is denoted as Equation 5 below:

ΔLOG FUELCOST$_t$ = A_0 + A_{00} U_{t-1} + A_1 TAF FPOLICY + A_2 ΔLOG OUTPUT$_t$ + A_3 ΔLOG PRICEFUEL$_t$ + A_4 ΔLOG PCAPITAL$_t$ + A_5 ΔLOG UPPER WINDQUALITY$_t$ + U_t (EQUATION 5)

where Δ is the first differences operator, for example,

ΔLOG FUELCOST$_t$ = LOG FUELCOST$_t$ - LOG FUELCOST$_{t-1}$

The model in Equation 5 above relates the change in fuel expenditures to the change in other variables and equilibrating error. The parameter, A_{00} measures the proportion of disequilibrium in fuel expenditures in one year corrected in the next year. - This parameter must be negative and has a value of between zero and one (i.e. one means 100% correction in the next period). The other parameters relate to short-run effects of the relevant economic variables on change in fuel expenditures.

(iii) Data Sources

Data on total fuel expenditures, available tonne-kilometres, revenue load factor and depreciation of aircraft were obtained from published annual reports of Qantas Airways Limited from 1971/72 to 1993/94. All data were crosschecked with several key administration personnel of the company to ensure that they were consistent. From 1972 to 1987, the financial year of the company started in April of the calendar year and ended in March of the next year. From 1987 onwards, the financial year was changed to July to June. Hence the 1987/88 annual company report was peculiar in that the statistics and economic performance figures of the company were reported for both 12 months (July 1987 to June 1988 and 15 months (April 1987 to June 1988) basis. The actual figures used in this study for 1987/88 were the adjusted figures for a twelve-month production cycle. Data on the wholesale prices of aviation turbine fuel in Australia were obtained from the Prices Surveillance Authority from August 1973 to December 1988. Data from 1989 onwards were obtained from the Bureau of Transport and Communications Economics, Canberra. Since Qantas purchased about half of its fuel overseas, U.S. dollar denominated aviation fuel prices were also used in the development of the model. These aviation jet fuel prices were obtained from Boeing Corporation Commercial Division, Seattle, Washington, U.S.A. Data on the mid-rate foreign exchange rates of the Australian dollar to the United States dollar were obtained from the Sydney office of the Reserve Bank of Australia. The foreign exchange rates were used to convert U.S. denominated aviation prices into Australian dollars.

CPI information was obtained from the Australian Bureau of Statistics. The CPI used from 1980 onwards was the weighted average of the eight capital cities in Australia (i.e. Sydney, Melbourne, Brisbane, Adelaide, Perth, Hobart, Canberra and Darwin). This weighted index was not available for periods before 1980. Hence the Sydney index was used for the period, 1972 to 1979. Data on terminal aerodrome forecasts were obtained from Australian Bureau of Meteorology Head Office. Data for upper atmosphere wind and temperature forecasts were obtained from Australian Bureau of Meteorology for the period, 1972 to 1988 and from United States National Weather Service and European Centre for Medium Range Forecasting, Great Britain for the 1988 to 1994 period.

IV Results

(i) Quality of Upper Atmosphere Wind and Temperature forecasts

Regression analysis of the log of root mean square errors for both upper atmosphere wind and temperature forecasts variables on a time trend indicated that the coefficient of the time variable was negative and statistically different from zero confirming the general improvement of these forecasts. The regression results are summarised below with the standard errors in parentheses.

$$\text{LOG UPPER WINDQUALITY} = \underset{(0.052)}{3.042} - \underset{(0.004)}{0.036}\ \text{TIME}$$

$$\text{LOG UPPER TEMPQUALITY} = \underset{(0.031)}{1.239} - \underset{(0.002)}{0.024}\ \text{TIME}$$

However while the overall accuracy of TAFs had been consistently high there had not been significant improvement in the quality either measured by the percentage of all forecasts correct which averaged about 88% or the proportion of no alternate forecasts issued by the Bureau of Meteorology that turned to have required alternate fuel (which averaged about 1.8%). The latter represented the possibility of diversions based on Qantas' current fuel policy.

(ii) Estimation of Fuel Expenditures Models

The results of the long run fuel expenditures econometric model specified by Equation 4 estimated by OLS were biased and inconsistent because the ADF test showed that all variables in the model were *not* stationary. The ADF test involved comparison of the t-statistics (calculated ADF statistics) to the critical values given by Mackinnon (1991). These results indicated that the variables were all integrated of the order I(1). Investigation of the cointegration of the variables using the Johansen (1988) procedure established that there were at least four cointegrating relationships among the variables specified in the long run total expenditures function. This meant that at least one-long-run equilibrating relationship existed. The long run equilibrium relationship of total fuel expenditures function was estimated using a version of OLS procedure whereby the standard errors of the parameters were corrected for heteroscedasticity. Estimates of the long run fuel expenditures function are reported in Table 1. They indicate that increasing output and price of aviation fuel led to increased fuel expenditures of the company. Increased capitalisation of the airline which involved the acquisition of newer more expensive fuel-efficient aircraft led to reduced real fuel expenditures. This result was consistent with view expressed by Qantas that more fuel-efficient planes reduced fuel expenditures by about 10% (B. Phair, personal communication, January 1995).

Because of possibility of short run disequilibrium, the fuel expenditures function was estimated using the ECM procedure. Since the estimation was based on first differences of the variables, the TAF fuel policy variable was a *pulse dummy variable* with a value of one in the 1986/87 financial year (the year of full compliance with the fuel policy change) and zero otherwise. The results of the ECM estimation are presented in Table 2. They indicate similar findings to those for Table 1 in terms of statistical significance of variables. However results in Table 2 show stronger statistical significance of the TAF fuel policy variable. Similar to Table 1, the upper atmosphere winds forecasts variable was shown in Table 2 to have had no significant effect on fuel expenditures. This insignificant effect of winds forecasts on fuel expenditures was probably due to masking of potential effect by *the yearly aggregated* data used for the analysis.

The TAF fuel policy change reduction factor was **$((1/e^{A1})-1)$** where **A_1** is the TAF fuel policy change dummy variable coefficient. For the level estimation of the long run fuel expenditures function reported in Table 1, it measured the proportional reduction of total fuel expenditures as a result of the policy change related to use of TAFs to decide the amount of fuel to be uplifted. The estimate of the TAF FPOLICY variable coefficient was **-0.228** (see Table 1). This figure translated to a 25.6% fuel reduction factor resulting from use of TAFs. Therefore the corresponding annual fuel expenditures saving as a result of the TAF fuel policy change was A$175.3 million for the 1993/94 financial year (i.e. 0.256*A$684.6 million).

For the estimation based on first differences using the short run function involving the ECM model, reported in Table 2, the relevant pulse dummy variable would measure a one-time shock (with permanent effect) on the mean value of the dependent variable (Enders, 1995, pp. 243-245); in this case the incremental change in annual fuel expenditures (or the first difference in annual fuel expenditures). The estimate of the pulse dummy variable coefficient for the fuel policy change was -0.178. This figure represented a 19.5% one-time permanent reduction in the expected incremental change in fuel expenditures as a result of the change in fuel policy which was fully implemented beginning in the 1986/87 financial year. The change in yearly fuel expenditures just before the full implementation of fuel policy change (in the 1985/86 financial year) to the year of full implementation of policy (1986/87 financial year) was a considerable decline of A$211.8 million in 1993/94 prices. The 19.5% reduction factor therefore represented about A$41.3 million (0.195 * 211.8 million) one-time permanent reduction in fuel expenditures based on the pulse dummy variable coefficient. Given the relatively high level of statistical significance of the pulse dummy variable coefficient reported in Table 2 compared to the low level of statistical significance for the level dummy variable reported in Table 1, the A$41.3 million reduction in annual fuel expenditures based on 1993/94 prices and using the pulse dummy variable is the more credible estimate of savings for use of TAFs. This estimate of annual fuel savings was within the range of A$20 to A$80 million suggested by the airline management as the likely range of savings based on their anedoctal evidence. It was also similar to the magnitude of cost savings established by Leigh (1995) using simulation modelling analysis.

Table 1: Results of long run fuel expenditures function for Qantas Airways Limited from 1971/72 to 1993/94.

Explanatory Variables	Coefficient Estimate	Standard Error	Probability Level of Significance**
CONSTANT	-3.478	0.717	0.001***
TAF FPOLICY	-0.228	0.147	0.139*
LOG OUTPUT	0.888	0.234	0.001***
LOG PRICEFUEL	0.838	0.179	0.001***
LOG PCAPITAL	-0.196	0.146	0.197*
WINDQUALITY (LOG)	0.084	0.079	0.305
Overall F	110.9***	Residual Sums of Squares	0.226
Adjusted R^2	96.2%	Durbin Watson Statistic	2.32

Notes:

*** significantly different from zero at the 1% level

** significantly different from zero at the 10% level

* significantly different from zero at the 20% level

Table 2: Results of short run behaviour of fuel expenditures function for Qantas Airways Limited from 1971/72 to 1993/94 based on estimation by ECM procedure.

Explanatory Variables	Coefficient Estimate	Standard Error	Probability Level of Significance**
CONSTANT	-0.017	0.045	0.702
U_{t-1}	-0.847	0.316	0.017***
TAF FPOLICY	-0.178	0.082	0.046***
ΔLOG OUTPUT	1.032	0.522	0.067**
ΔLOG PRICEFUEL	0.734	0.227	0.006**
ΔLOG PCAPITAL	-0.207	0.150	0.187*
ΔLOG WINDQUALITY	0.132	0.140	0.360

Overall F	12.39***	Residual Sums of Squares	0.182
Adjusted R^2	76.3%	Durbin Watson Statistic	2.06

Notes:

*** significantly different from zero at the 1% level

** significantly different from zero at the 10% level

* significantly different from zero at the 20% level

V Conclusion

A total fuel expenditures function was estimated by multiple regression techniques using annual data from 1971/72 to 1993/94 with total annual fuel expenditures as dependent variable and independent variables being price of aviation fuel, airline output, capitalisation measured by annual depreciation of aircraft, fuel policy of the airline with regards to the use of TAFs to uplift alternate fuel and quality index of upper atmosphere wind forecasts. Results indicated that, as expected from economic theory, the price of aviation fuel and airline output had strong positive impact on the airline fuel consumption. Increased capitalisation through the acquisition of more fuel-efficient planes appeared to have led to reduced fuel consumption. The fuel policy change with regards to TAFs, instituted in late 1985, of carrying alternate fuel based on weather forecasts, was shown to have been beneficial to the airline saving the company about A$41 million annually in reduced fuel consumption. The effect of increasing quality of upper atmosphere wind forecasts on airline fuel consumption was not proven in this study. This might possibly be due to the limited amount of available data and the high degree of data aggregation (using yearly data) which could have masked potential significant effects of upper air winds forecasts on fuel consumption. Monthly verification data on TAFs and upper wind forecasts are available from various Bureaux of Meteorology. It would therefore be useful if Qantas maintains monthly economic data on fuel expenditures and output in order to clearly establish the effect of quality of aviation weather forecasts such as upper atmosphere wind forecasts. The derived fuel savings captured other effects from related weather services such as TTFs and Code Grey warnings which were not analysed because of lack of verification data.

Overall this study seemed to support the management decision of Qantas Airways Limited in continuing its alternate fuel policy with regards to the use of TAFs even though it remains one of the few airlines carrying out such a policy. General safety has not declined while it has obtained considerable savings in reduced fuel expenditures. In addition minor adjustments to the fixed and variable fuel reserves undertaken since 1985 appeared to suggest that the company is comfortable with its alternate fuel policy. This study using actual airline data and weather forecast verification data has shown the direct economic benefits of aviation weather forecasts. These direct economic benefits combined with the non-quantifiable value related to airline and public safety demonstrate considerable value to society of weather forecasts for civil aviation. Given the high accuracy of TAFs as measured by the proportion of those forecasts classified as correct, improvements of TAFs to reduce likelihood of diversions caused by inaccurately forecast alternate fuel weather conditions seem to be an important area of research especially with regards to the prediction of fogs and winds. Continuous development of new aviation weather products and services, such as the Code Grey warning system currently used by Qantas as additional information to uplift alternate fuel, is also desired. The establishment of relevant verification data for important weather services would be useful in determining the economic benefits of aviation weather services.

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