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An Evaluation of Aircraft Emissions Inventory Methodology by Comparisons With Reported Airline Data

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EXECUTIVE SUMMARY

This report provides results of work done to quantify the effect of assumptions used in calculations of aircraft emissions inventories. Calculations made using the inventory methods are compared to actual aircraft fleet fuel consumption data. Results are also presented that show the sensitivity of calculated emissions to aircraft payload factors.

Comparisons were made between U. S. Department of Transportation (DOT) Form 41 data reported for 1992 and aircraft emission inventory methods. For the ten major passenger air carriers considered, there was good agreement between the DOT Form 41 data and values calculated as part of the NASA 1992 scheduled inventory for total aircraft departures and miles flown. This increases confidence in the assumption that the OAG derived flight schedule used to create the NASA 1992 scheduled emissions inventory gives an accurate accounting of passenger flights that actually took place. Total fuel consumption calculated as part of the NASA 1992 scheduled inventory was, on the average, 17% below that reported on DOT Form 41 for the ten major passenger air carriers considered. Differences between fuel consumed per mile for general aircraft types (i.e. 737, 747) calculated from 1992 DOT Form 41 data and that calculated from the 1992 NASA scheduled inventory were not a strong function of the size of the aircraft.

For the cargo air carriers considered in the analysis of the DOT Form 41 data, departures and ground track miles did not match well between the 1992 inventory results and the DOT Form 41 data set. This indicates that the OAG flight schedule used to create NASA scheduled aircraft emissions inventories may not accurately account for some cargo flights. Because the fuel consumed by the cargo portion of the scheduled aircraft fleet is relatively small, the effect of inaccuracies in the cargo schedule on scheduled inventory results is likely to be small.

Analysis of in-flight fuel flow data for one operator's 747-400 fleet was conducted. Three major areas were identified that would lead to higher observed aircraft fuel consumption by the operator's 747-400 aircraft relative to the inventory model. These were, increased distance flown, increased weight, and possible deterioration effects. The studied aircraft flew an average of 3.8% equivalent further distance (accounting for winds aloft) than the most direct route. This would translate to an increase in fuel consumption of 4.7% on a 5000 mile mission. The operator's fleet was on average 11.2% heavier during cruise. This would translate to an increase in fuel consumption of around 9.0% for a 5000 mile mission. Lastly, if fuel mileage for this operator's fleet follows typical deterioration trends considering this type of aircraft and aircraft age, then a decrease in fuel mileage of about 3.6% would be projected. This would add 4.2% more fuel use. In all, for a sample 5000 mile mission, the inventory model will predict a 17.9% increase in fuel consumption when assuming 747-400 fleet operating characteristics that are similar to those of the carrier considered in this analysis. While this difference is similiar to the results presented in the DOT Form 41 data comparison, further study is required of other operators, route structures and aircraft types before any broad

conclusions should be drawn. The other operating assumptions were not found to have significantly impacted fuel use. Shorter range aircraft will probably exhibit different operating characteristics than those of the 747-400 listed because they carry less cargo and will likely be more heavily impacted by air traffic control constraints. Additionally, no significant seasonal variations were found with this operator's 747-400 fleet.

Aircraft payload varies by route, operator and over time. Scheduled emissions inventories assume a constant payload (e.g. 70% passenger load factor plus allowance for baggage, no freight, no mail) for all carriers, all routes and for different years. An investigation was done of the variation in fuel use and NOx emissions as a function of payload in order to understand the potential range of emissions distribution, both from a global total standpoint and a spatial standpoint. As part of this investigation, fuel use and NOx emissions for four aircraft/engine combinations were studied as a function of payload. Total NOx and CO_2 were shown to vary linearly with payload. Analysis of 747-400 data showed that factors for scaling CO_2 and NOx for different loadings created using single mission data for a given aircraft may be useful in scaling global or regional totals of these emittants. When applying these scale factors on a cell by cell basis to three dimensional global emissions inventory results, incorrect spatial distributions of global emissions are expected to result because of flight altitude changes and changes in fuel burn rate.

Further study of in-service aircraft to account for more aircraft types and different typical missions will contribute to a better understanding of the effects of actual operations including air traffic control, variations in payload, cargo, and meteorology.

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GLOSSARY

AD	Actual Distance
AEAP	Atmospheric Effects of Aviation Project
ATC	Air Traffic Control
BKK	Bangkok International Airport (Thailand)
BOM	Bombay International Airport (India)
CAEP	ICAO Committee on Aviation Environmental Protection
CFR	United States Code of Federal Regulations
DOT	United States Department of Transportation
EI_{NOx}	Emissions index for NOx given as grams of NOx/Kg fuel
GADS	Global Aviation Data Set
GC	Great Circle
GS	Ground Speed
HKG	Hong Kong International Airport
ICAO	International Civil Aviation Organization
ISA	International standard atmosphere
JFK	John F. Kennedy International Airport (USA)
JNB	Johannesburg International Airport (South Africa)
kg	kilogram
kts	nautical miles per hour
LAX	Los Angeles International Airport (USA)
lb	pound
LF	Load Factor
LHR	London Heathrow International Airport (UK)
Load Factor	Percentage of an airplane's seat capacity occupied by passengers
LRC	Long Range Cruise
MIA	Miami International Airport
MTOW	Maximum Take-Off Weight
NASA	National Aeronautics and Space Administration (USA)
NAM	Nautical Air Mile
nmi	Nautical mile
NRT	Narita International Airport (Japan)
OAG	Official Airline Guide
P&W	Pratt & Whitney
PAX	passengers
RR	Rolls-Royce
SAD	Equivalent Still Air Distance (TAS x Time)
SFO	San Francisco International Airport (USA)
SIN	Singapore International Airport (Malaysia)
st-mi	Statute Mile
std	Standard
TAS	True Air Speed
TOGW	Takeoff gross weight

1.0 INTRODUCTION

Much research has been, and is currently being, done throughout the world to understand the global atmospheric effects of pollutants emitted by the world's aircraft fleet at cruise altitudes. The majority of this research has been conducted under the NASA Atmospheric Effects of Aviation Project (AEAP) and the European EC/AERONOX projects. In support of both of these projects, various three dimensional global emissions inventories for the world's subsonic aircraft fleet have been calculated. These inventories give the distribution of aircraft emissions (NOx, CO, and total hydrocarbons) and fuel burned throughout the global atmosphere. Results of these inventories are used as input to chemical transport models which in turn are used to estimate the effects of aircraft emissions on the global climate.

Under the NASA AEAP program, scheduled jet aircraft and turboprop aircraft emissions inventories for 1976, 1984 and 1992 have been produced (ref. 1,2) and a projection for the year 2015 has been done (ref. 3). In support of the EC/AERONOX program, global emissions inventories for 1991/1992 and projections for 2015 have been produced by the Group of Experts on the Abatement of Nuisances Caused by Air Transport (ANCAT) (ref. 4). In order to calculate these global emissions inventories and projections, and make them computationally feasible, simplifying assumptions regarding the performance and operation of aircraft must be made. These simplifying assumptions introduce some uncertainty to the calculation of global emissions and fuel burn.

This study evaluates the effects of simplifying assumptions made about airplane performance when calculating the emissions inventories used to support the NASA AEAP research program. These assumptions are as follows:

- No winds
- International Standard Atmosphere (ISA) temperatures and pressures
- Continuous climb cruise flight segment with typical westbound flight beginning and ending cruise altitudes
- No cargo (Payload = passengers + baggage weight)
- 70% passenger load factor
- Passenger and baggage weight equals 200 lb/passenger for single aisle and 210 lb/passenger for wide body aircraft
- Boeing typical weight calculations used for Operating Empty Weight, Maximum Landing Weight, Maximum Zero Fuel Weight, etc.
- Fuel density of 6.75 lb/gallon, fuel energy content of 18,580 BTU/lb
- Direct great circle routes--no turns or air traffic control diversions
- Takeoff Gross Weights (TOGW) are calculated assuming city pairs are at sea level. Performance calculations assume origin and destination airports are at their respective actual airport altitudes.

- Optimum aircraft operating rules
- Engine and airframe performance at new airplane level

An attempt is made in this study to quantify the differences between calculated and actual fuel use that occur because of the above simplifying assumptions. The most likely factors leading to these differences are then identified and investigated.

The first part of this report focuses on how accurately the NASA global emissions inventory methodology predicts total fuel burn for aircraft fleets of selected airlines. A comparison is made between fuel burn calculated as part of the NASA 1992 global emissions inventory and 1992 airline fuel consumption data reported to the U. S. Department of Transportation via DOT Form 41.

In the second part of this report, the simplifying assumptions having the greatest effect on discrepancies between calculated and actual fuel burn are identified and investigated. This is accomplished by comparing results of performance calculations done using assumptions made in the NASA scheduled fleet emissions inventory work with actual data obtained from in-service 747-400 aircraft. The most significant factors contributing to these differences are presented and sensitivities established.

The third part of this report focuses on the effects of assumed cargo and passenger loading on mission fuel burn and NOx calculation results. Details of a parametric study on the effect of aircraft take-off gross weight on aircraft mission fuel burn and NOx are presented.

The technical work described here was primarily performed by David L. Daggett and Donald J. Sutkus. Steven L. Baughcum was the principal investigator for the task and performed some of the initial scoping calculations. Douglas P. DuBois provided guidance in analysis of the GADS data set and Terrance G. Tritz was responsible for preliminary analysis of DOT Form 41 data.

2.0 FLEET FUEL USE ANALYSIS

2.1 Preface

The historical NASA scheduled aircraft fleet global emissions inventories discussed in the previous section of this report were created using Official Airline Guide (OAG) flight schedule data, Boeing aircraft performance data and International Civil Aviation Organization (ICAO) engine emissions data. A simplified airplane performance calculation was used to determine the fuel burn rate at points along the flight path and from this, emissions of NOx, CO and total hydrocarbons at these points were calculated. These emissions were then distributed on a 1 degree by 1 degree by 1 km grid to create a three-dimensional global emissions inventory for the scheduled aircraft fleet. A detailed discussion of the process used to create NASA global emissions inventories has been published previously (ref. 2).

When aircraft emission inventories are created, certain simplifying assumptions must be made about the conditions under which aircraft operate in order to make the calculation of global emissions inventories computationally feasible. These assumptions, which were listed in the previous section, lead to inaccuracies in the calculation of global aircraft fleet fuel consumption and emissions in the inventory calculations.

Some of the characteristics of the OAG flight schedule data used in creating the NASA scheduled aircraft fleet emissions inventories also lead to inaccuracies in global aircraft emissions inventory calculations. The historical NASA scheduled aircraft fleet global emissions inventories are based on the OAG listing of flights which is used as a resource for travelers attempting to book flights and was not designed with the intent of supporting global aircraft emissions studies. Flights listed in the OAG are those that are *scheduled* to take place and not ones that actually occurred. In addition, the OAG flight schedule often contains duplicate listings of the same flights due to phenomena such as codesharing between airlines. Filtering of the OAG schedules must be done prior to their use for calculating emissions inventories and the filtering process is another possible source for inaccuracies in emissions inventory results.

An assessment of the magnitude of inaccuracy introduced to the scheduled aircraft emissions inventory by the sources discussed above was conducted. A comparison was done between results of the NASA 1992 scheduled fleet global emissions inventory and aircraft traffic and fuel use statistics for 1992 given on the United States Department of Transportation (DOT) Form 41. Details of this comparison are discussed in the subsections below.

2.2 DOT Form 41 Data Description

Each large U.S. air carrier must file DOT Form 41 Schedule T-2 on a quarterly basis. Details of reporting requirements are documented in Reference 5. The form contains air carrier traffic and capacity broken down by specific aircraft type (i.e. 747, DC-10 etc.) and geographic region where flights took place (i.e. North

America, Atlantic Ocean, etc.). The data contained on DOT Form 41 is for U.S. domestic flights and flights flying into and out of the U.S. only.

The reported items from DOT Form 41 used for comparison with results of the NASA global emissions inventory for the 1992 scheduled aircraft fleet were: aircraft fuel issued (U.S. gallons), revenue aircraft departures performed and revenue aircraft statute ground track miles flown. Revenue aircraft ground track miles flown, as reported on the form, were calculated by taking the great circle distance between each airport pair flown and multiplying it by the number of departures scheduled between that particular airport pair. The reported item of revenue aircraft departures performed gives the actual number of revenue departures that were performed as reported by each individual air carrier. The aircraft fuel issue statistics given on DOT Form 41 represented the airline's best estimate of the actual aircraft fuel use for the departures listed on the form.

2.3 Methodology

DOT Form 41 fuel issue, departure and ground track miles flown data given by airplane type was obtained for the 1992 calendar year for each of the 69 domestic air carriers that were required to report traffic and capacity data to the U.S. Department of Transportation. Detailed comparisons between the two data sets were made for ten major air carriers who carry passengers on the majority of their flights (passenger carriers). These ten air carriers were responsible for 88% of the total fuel consumption reported by all of the air carriers that reported DOT fuel consumption data in 1992. An attempt was also made to make comparisons between the two data sets for airlines that carry only cargo on a majority of their flights (cargo carriers), but results of this comparison were not conclusive. Although DOT Form 41 data was broken down by specific geographic region, only totals over all regions were considered in this analysis.

For each of the air carriers considered in this comparison, inventory flight schedule files were extracted for each month of 1992. All the flights for each airline were then matched to the respective airframe/engine performance, and engine emission characteristic. The total annual fuel use was then calculated using the same methodology and computer program that was used to calculate the 1992 aircraft emission inventories (ref. 2). Yearly departures, ground track miles flown and amount of fuel consumed were totaled by aircraft type for each carrier. Data listed on DOT Form 41 for each carrier were matched to those on the 1992 inventory list when possible and total departures, ground track miles flown and fuel consumed were compared for each aircraft type on a percent difference basis.

Fuel consumed per mile flown was calculated for each general aircraft type in both of the data sets by dividing fuel consumed by great circle distance flown. Final comparisons between the DOT Form 41 data and the 1992 scheduled inventory were done on both an air carrier fleet basis and a general aircraft type basis. For the air carrier fleet comparison, departures, ground track miles and fuel consumption numbers for each general aircraft type in the carrier's fleet were totaled. Percent differences between the two data sets for departures, ground track miles, total fuel consumption and fuel consumed per mile were calculated using the DOT Form 41 data as the basis.

2.4 Results and Discussion

Table 2.1 and Figure 2.1 show the results of the comparison of yearly totals for departures, ground track miles flown, fuel consumption and fuel consumption per mile between the 1992 DOT Form 41 data and the 1992 emissions inventory for the ten passenger air carriers considered. Comparisons are made on a percent difference basis relative to the DOT Form 41 reported values. A negative percent difference therefore signifies 1992 emissions inventory values that are lower than those reported on DOT Form 41.

Table 2.1 and Figure 2.1 show that total departures and ground track miles flown agree within 3.5% for all of the ten passenger air carriers considered and that, for the majority of carriers, they agree within 2.5%. Departures and ground track miles totaled over the ten carriers agree within 1.1%.

Agreement in departures indicates that the number of operations is correct while agreement between ground track miles flown indicates that the correct city pairs have been modeled. The close agreement for passenger air carriers between the two data sets on yearly departures and ground track miles validates the accuracy of the processed flight schedule data used to generate the NASA 1992 global emissions inventory for the scheduled passenger aircraft fleet.

Cargo carriers accounted for 6% of the fuel consumption reported on DOT Form 41 by all U. S. airlines in 1992. Departures and ground track miles did not match well between the 1992 inventory results and the DOT Form 41 data set for cargo carriers. Percent differences between the two data sets for departures ranged between +25% and -75%. This large difference is due either to errors in DOT Form 41 data reporting or to inaccuracies with the way in which cargo flights are represented in the OAG flight schedule data used to create scheduled aircraft fleet emissions inventories. It is likely that the majority of the difference is due to the latter.

Because the cargo portion of the scheduled fleet is relatively small from a fuel burn standpoint, the effect of inaccuracies in the OAG schedule for cargo aircraft on inventory results will be relatively small. Nonetheless, more work will need to be done in the future to understand the cause of this mismatch and to better quantify its impact on NASA scheduled emissions inventory results, and whether more recent schedules still exhibit this anomaly.

Table 2.1. 1992 DOT Form 41 and 1992 NASA Scheduled Emissions Inventory Annual Traffic and Fuel Statistics for Selected Air Carriers

	Departures			Distance* (statute miles)			Fuel (U.S. gal.)			Fuel/Mile (U.S. gal./mile)		
Air Carrier	DOT	Inventory	% Diff.	DOT	Inventory	% Diff.	DOT	Inventory	% Diff.	DOT	Inventory	% Diff.
Alaska	1.17E+05	1.17E+05	-0.4%	7.61E+07	7.56E+07	-0.5%	2.10E+08	1.76E+08	-16.2%	2.77E+00	2.33E+00	-15.8%
America West	1.94E+05	1.95E+05	0.2%	1.27E+08	1.27E+08	0.0%	2.99E+08	2.49E+08	-16.7%	2.35E+00	1.96E+00	-16.7%
American	9.32E+05	9.22E+05	-1.0%	8.65E+08	8.57E+08	-0.8%	2.86E+09	2.33E+09	-18.7%	3.31E+00	2.71E+00	-18.0%
Continental	4.90E+05	4.90E+05	0.1%	4.19E+08	4.21E+08	0.4%	1.33E+09	1.10E+09	-17.4%	3.17E+00	2.61E+00	-17.8%
Delta	1.05E+06	1.06E+06	0.7%	7.94E+08	7.96E+08	0.3%	2.81E+09	2.31E+09	-17.9%	3.54E+00	2.90E+00	-18.1%
Northwest	5.37E+05	5.48E+05	1.9%	4.67E+08	4.76E+08	2.0%	1.85E+09	1.52E+09	-17.9%	3.96E+00	3.19E+00	-19.5%
Southwest	4.39E+05	4.47E+05	1.8%	1.67E+08	1.68E+08	1.0%	3.98E+08	3.45E+08	-13.3%	2.39E+00	2.05E+00	-14.1%
TWA	2.74E+05	2.81E+05	2.5%	2.28E+08	2.34E+08	2.5%	9.35E+08	7.54E+08	-19.4%	4.10E+00	3.22E+00	-21.4%
United	7.22E+05	7.32E+05	1.5%	6.95E+08	7.04E+08	1.2%	2.53E+09	2.11E+09	-16.6%	3.64E+00	3.00E+00	-17.6%
US Air	9.27E+05	9.58E+05	3.4%	4.79E+08	4.89E+08	2.1%	1.19E+09	9.82E+08	-17.5%	2.49E+00	2.01E+00	-19.2%
Totals	**5.68E+06**	**5.75E+06**	**1.1%**	**4.32E+09**	**4.35E+09**	**0.7%**	**1.44E+10**	**1.19E+10**	**-17.7%**	**3.17E+01**	**2.60E+01**	**-18.1%**

* Ground track statute miles

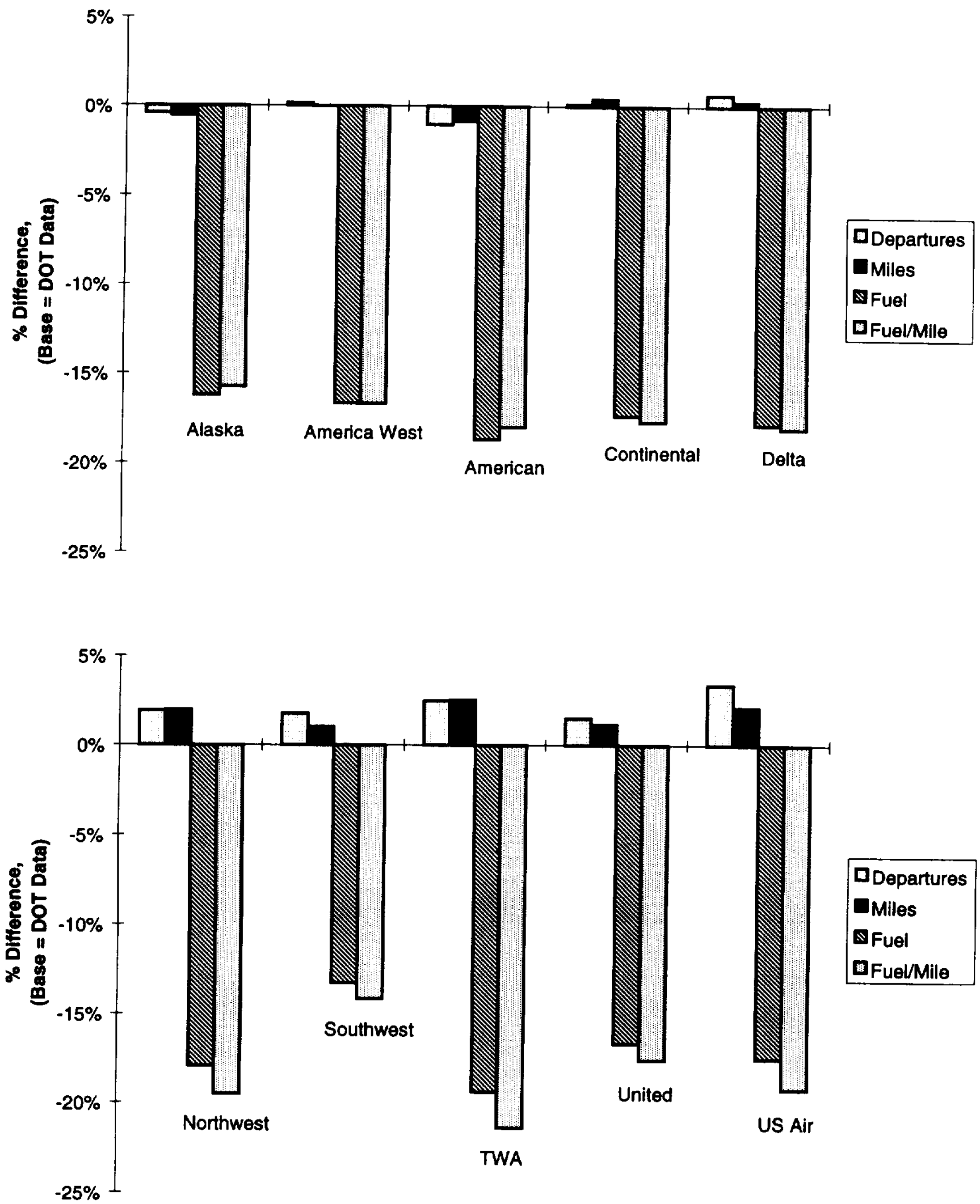


Figure 2.1. Comparison of 1992 DOT Form 41 and 1992 NASA Scheduled Emissions Inventory Annual Traffic and Fuel Statistics for Selected Air Carriers

Because the departures and ground track miles agree well between the DOT Form 41 data and the NASA 1992 scheduled inventory for the passenger carriers listed in Table 2.1, a valid comparison between fuel consumption numbers can be made. For the passenger air carriers listed in Table 2.1, percentage differences between total fuel consumption and fuel consumption per mile fall in a fairly narrow band. The standard deviations between the ten passenger carriers listed in Table 2.1 for total fuel consumption and fuel consumption per mile percent differences are 1.7% and 2.0% respectively.

The average fuel weighted percent difference between the two data sets for total fuel consumption is -17.7% and the average fuel weighted percent difference for fuel consumption per mile between the data sets is -18.1%. The total fuel consumption and fuel consumption per mile values calculated as part of the 1992 scheduled fleet inventory are likely lower than those from DOT Form 41 because of the simplifying assumptions made during the emissions inventory calculation process which were outlined in Section 1.0 of this report. Section 3.0 of this report examines some of the specific assumptions that may have contributed to these results.

Figure 2.2 shows the average percent differences between DOT Form 41 and NASA scheduled inventory fuel consumption per mile data for nine general aircraft types. The values plotted in this figure were obtained by selecting percent differences in fuel consumption per mile for the carriers that had the general type of aircraft in their fleet. For each general aircraft type, a weighted average of the percent difference between fuel consumption per mile reported on DOT Form 41 and that calculated as part of the NASA 1992 scheduled inventory was taken to arrive at the values plotted in Figure 2.2. The weighted average was based on the fuel consumed by the general aircraft type in each carrier's fleet. Error bars in this figure show the plus and minus one standard deviation variance present over the different carriers in the fuel consumption per mile values for each airplane type. General aircraft types are listed in order of typical Maximum Take-Off Weight (MTOW) from left to right.

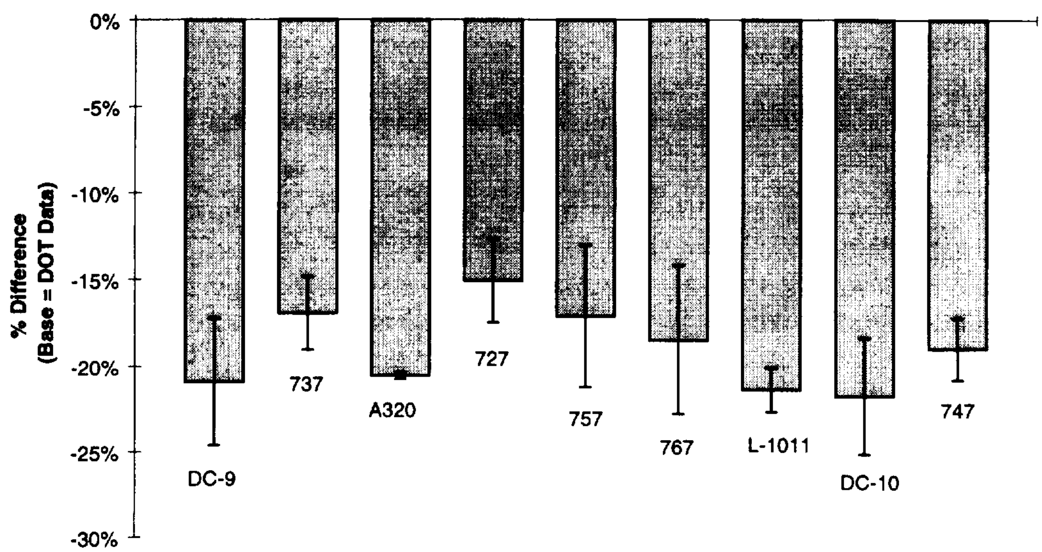


Figure 2.2. Average Percent Difference in Fuel Consumed Per Mile for Selected General Aircraft Types

Figure 2.2 shows that differences between fuel consumed per mile, calculated from 1992 DOT Form 41 data, and those calculated from the 1992 NASA scheduled inventory are not a strong function of the size of the aircraft. The relatively large error bars on the data show that the average fuel consumed per mile for a general aircraft type can vary significantly from one carrier to the next. This may be due to differences in the typical payloads carried by a general aircraft type or to differences in the mix of specific aircraft types (i.e. 747-200, 747-400) in a particular air carrier's fleet of a general aircraft type (i.e. 747). Differences in route structure (long range versus short range flights) will also be important.

2.5 Fleet Fuel Use Analysis Findings

For each of the ten major passenger air carriers considered in this analysis, there was good agreement (within 3.5%) between aircraft departures and ground track miles flown reported on DOT Form 41 and those that were calculated as part of the NASA 1992 scheduled inventory. Aircraft departures and ground track miles totaled over all ten of the passenger air carriers considered agreed to within 0.7% and 1.1% respectively. The very close agreement in these numbers increases confidence in the assumption that the processed (ref. 2) OAG derived flight schedules used to create the NASA 1992 scheduled emissions inventory gives an accurate accounting of passenger flights that actually took place. It can therefore be concluded that the accuracy of passenger flight schedules is not a factor that limits the overall accuracy of the NASA scheduled aircraft fleet emissions inventories, at least for flights within, to or from the United States.

For the cargo air carriers considered in this analysis, departures and ground track miles did not match well between the 1992 inventory results and the DOT

Form 41 data set. This indicates that the OAG flight schedule used to create NASA scheduled aircraft emissions inventories may not accurately account for some cargo flights. Although the effect of inaccuracies in the cargo schedule on scheduled inventory results is likely to be small, more investigation will be necessary in the future to better understand this problem.

Total fuel consumption calculated as part of the NASA 1992 scheduled inventory was on the average 18% below that reported on DOT Form 41 for the ten major passenger air carriers considered. The majority of this difference is likely due to the simplifying assumptions made regarding the performance calculations used in creating the NASA 1992 scheduled aircraft emissions inventory. Major factors here are assumed payload, cargo load, the effect of air traffic control, and the assumption of great circle routing. Some of these factors will be addressed for one airline's 747-400 fleet in Chapter 3.

Differences between fuel consumed per mile, as calculated from 1992 DOT Form 41 data, and that calculated from the 1992 NASA scheduled inventory were not a strong function of the size of the aircraft.

3.0 AIRCRAFT FUEL USE ANALYSIS

Section 2.0 showed that there are fuel use discrepancies between the calculated and reported commercial aircraft fleet. This section will explain how different operating conditions impact jet airplane fuel consumption by comparing modeled performance data with recorded observations.

3.1 Aircraft Data Description

Cruise performance data from an operator's fleet of Boeing 747-400 aircraft are compared to what would be predicted using the inventory model assumptions mentioned in section 1.0. Results of the comparison will show how each of the performance variables impact fuel use, their relative importance, and how closely the modeled variables match observed trends.

Data for this study was obtained from two sources; internal Boeing 747-400 aircraft performance data that reflects inventory performance calculation methods, and a Global Aircraft Data Set (GADS) that consists of actual 747-400 aircraft cruise flight performance data.

3.1.1 Inventory Method Data Source

The calculated commercial aircraft fleet inventory model was generated by a computer program that uses input from Boeing airplane performance models and the Official Airline Guide (OAG) flight schedule. During generation of the inventory, simplifying assumptions are used in creating a standard operating baseline. A summary of the fuel used is then available to the analyst. The inventory modeled aircraft flight tracks are based on great circle routes. Ten city-pair routes were chosen for study (to be discussed further in 3.1.2) and are shown in the figure below.

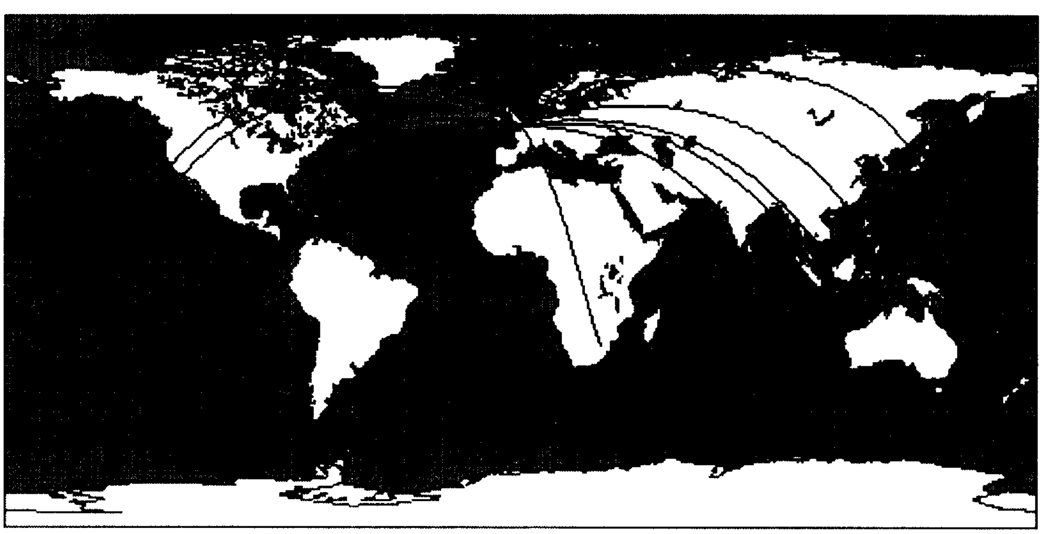


Figure 3.1. Great Circle Routes for studied 10 city-pairs

3.1.2 GADS Data Source

The data source for GADS comes from aircraft performance numbers normally generated and stored on board standard Boeing 747-400 Flight Management Computers (FMC).

One large aircraft operator's fleet of 747-400 aircraft was examined for the months of February 1997 and July 1998. These aircraft have either Rolls-Royce RB211-525G or RB211-524H engines. 747-400's typically seat 416 passengers in a three-class arrangement.

There were 1,269 recorded flights to 29 cities in the February GADS files as is illustrated in figure 3.2. Of these, 121 were missing airport descriptions and 9 were missing data leaving 1,139 useful flights. 873 of the flights originated or ended at London Heathrow Airport. Of these flights, 10 city pair flights had high enough frequency to account for 55% of all the 1,139 useful flights and are used as the basis for analysis in the report.

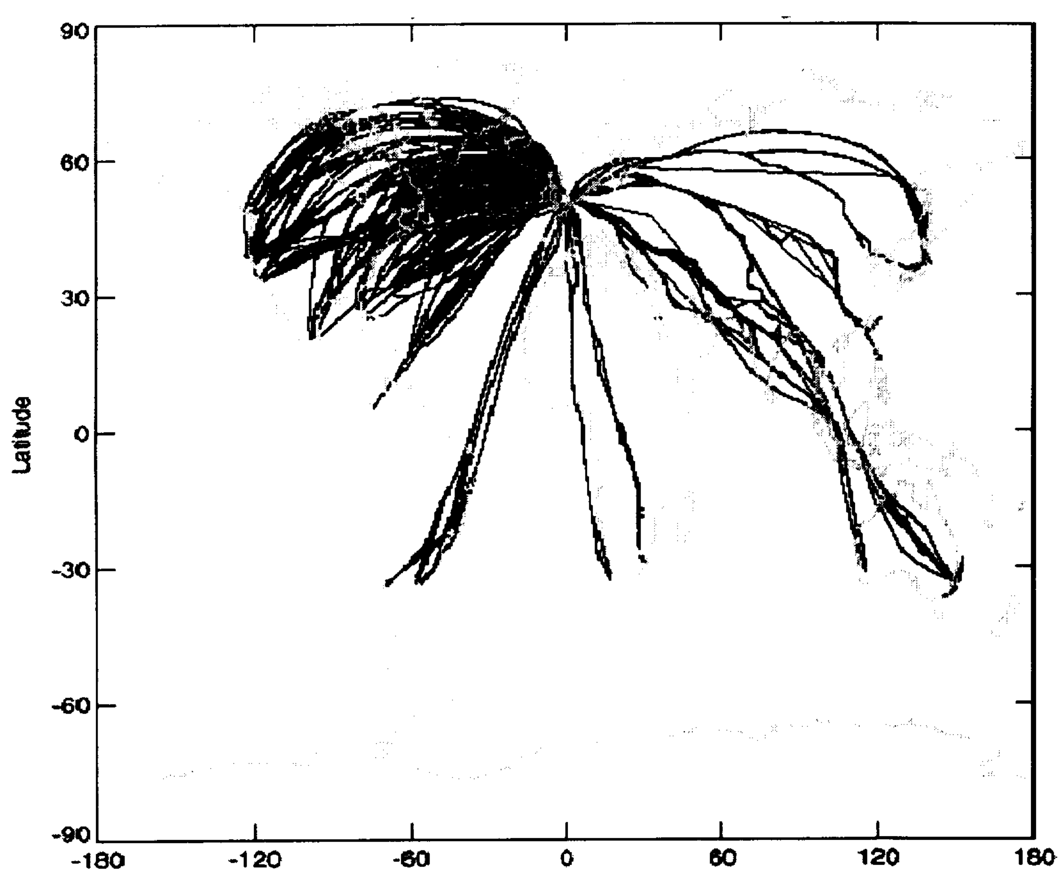


Figure 3.2. GADS Flight Tracks for all February 1997 Recorded Operations

Estimated aircraft gross weight is logged by the pilot prior to take-off and is updated by the FMC through fuel burn readings. Latitude and longitude, along with other performance data, are also recorded and were later used to calculate fuel mileage. Data filtering was used to compensate for observed erratic gross weight readings as shown in figure 3.3. In order to make analysis of the data tractable, the first three changing data points were averaged together to establish a starting cruise gross weight and the last three cruise changing points were averaged together for an ending weight. The beginning and ending numbers were then averaged to establish a mean cruise gross weight.

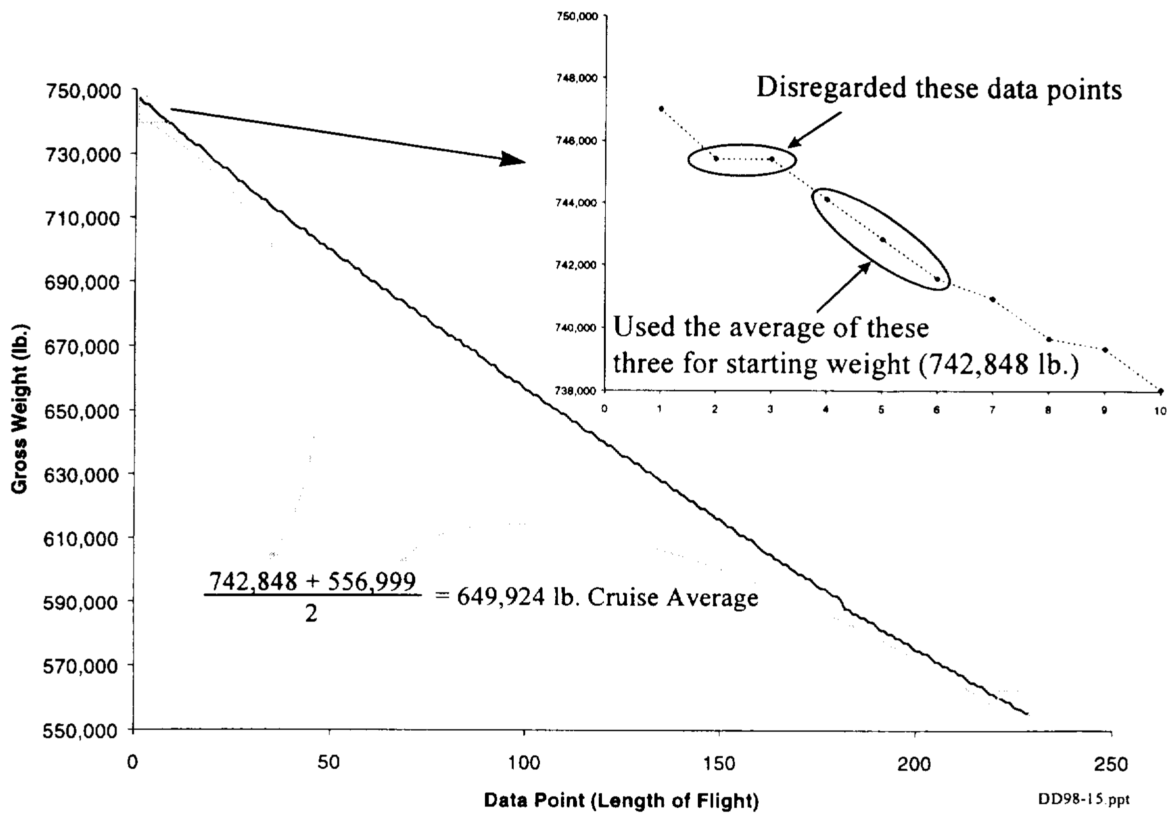


Figure 3.3. Data Filter Example of Gross Weight Recordings

Observation of the winds aloft and ground speed data also showed discrepancies as illustrated in figure 3.4. Comparison of the aircraft's true air speed versus ground speed minus tailwind shows that these two numbers diverge randomly. It is not believed that the aircraft's true air speed is changing significantly as there is not a corresponding change in engine fuel consumption. Thus, the data quality of winds aloft and/or ground speed are in question. As a result, distance traveled, time and true airspeed are used as measures of speed and derived head winds.

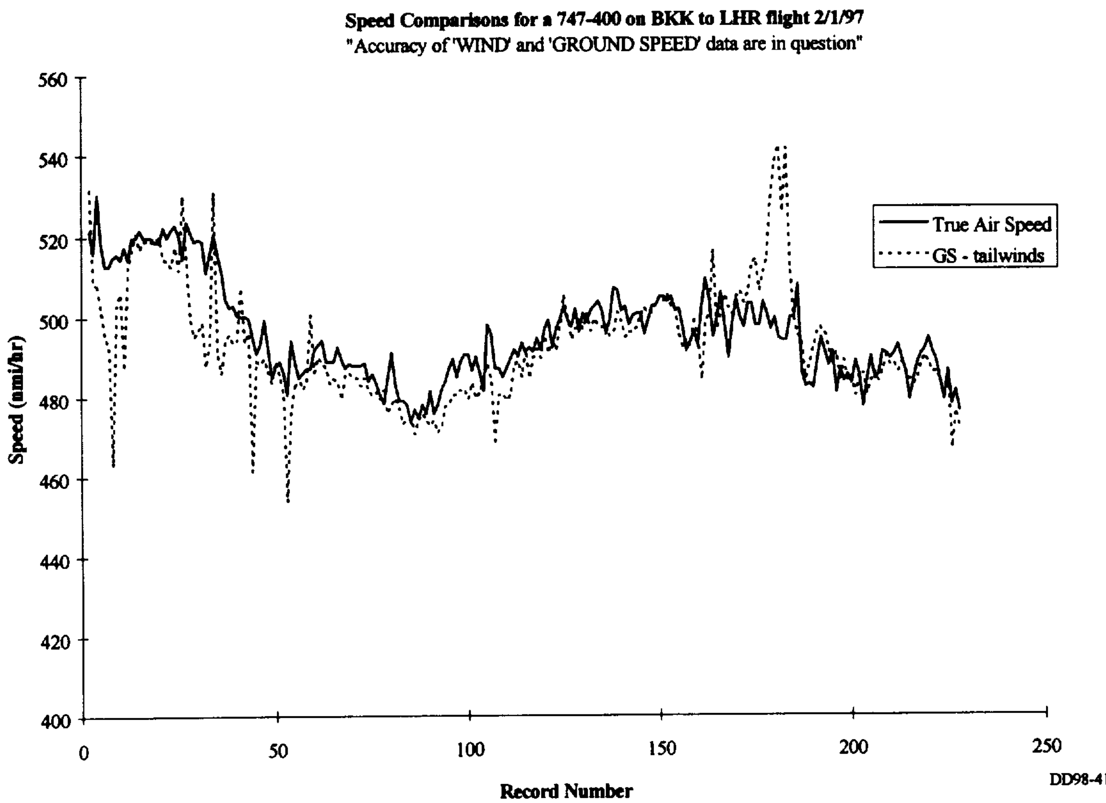


Figure 3.4 Wind and Ground Speed Recording Discrepancy

Passenger load factor and cargo weight are not recorded in the database. However, averages for each route were obtained through operator reported figures listed in ICAO statistics (ref. 6,7).

3.2 Aircraft Data Analysis

Factors that affect mission fuel consumption were analyzed. These included effective distance traveled, aircraft gross weight, altitude, ambient temperature, airplane cruise speed and fuel mileage. The GADS deviations from modeled conditions were calculated and sensitivity results are presented in section 3.3.

3.2.1 City-pair Distance

Due to the GADS recording constraints listed in Section 3.1.2, the distances used between the selected city-pairs were based on the cruise portion of each mission.

3.2.1.1 Inventory Method Distance

The inventory method chooses the most direct flight path between the airport city-pairs being modeled, which is a Great Circle route. The airport location, designator name, altitude, and great circle distance between London Heathrow airport (LHR) and each of the city-pair airports is shown in Table 3.1. The cruise portion of the distance will be less than that listed below.

Table 3.1. Studied Airports Summary and Great Circle Distances from LHR

Number	Designator	Latitude	Longitude	Altitude (ft)	City	Country	Distance (nmi)
1	BKKBKK	1354N	10036E	9	BANGKOK	THAILAND	5,167
2	BOMBOM	1905N	07252E	36	MUMBAI/BOMBAY	INDIA	3,881
3	HKGHKG	2219N	11412E	15	HONG KONG	HONG KONG	5,219
4	JFKNYC	4038N	07346W	13	NEW YORK	NEW YORK, USA	3,000
5	JNBJNB	2607S	02814E	5557	JOHANNESBURG	SOUTH AFRICA	4,887
6	LAXLAX	3356N	11824W	126	LOS ANGELES	CALIFORNIA, USA	4,763
7	MIAMIA	2547N	08017W	11	MIAMI	FLORIDA, USA	3,862
8	NRTTYO	3544N	14023E	139	TOKYO	JAPAN-NARITA	5,206
9	SFOSFO	3737N	12222W	11	SAN FRANCISCO	CALIFORNIA, USA	4,679
10	SINSIN	0121N	10359E	22	SINGAPORE	SINGAPORE-CHANGI	4,949

3.2.1.2 GADS Distance

For the purposes of this study, both inventory and GADS airplanes were considered to be at cruise conditions upon reaching a 29,000 foot altitude and until they started their descent to the final destination. Analysis of the GADS flight tracks revealed that in-service aircraft were rarely flying great circle routes. Figure 3.5 illustrates flights TO Bangkok (BKK), which have one of the most circuitous routes (8.4% or 407 miles farther than Great Circle) of the 10 studied city-pairs.

Figure 3.6 illustrates that flights TO and FROM LHR and John F. Kennedy Airport (JFK) follow different flight tracks. The studied flights TO JFK followed longer over-land routes.

Several factors account for in-service aircraft flying farther than the most direct route; mountainous terrain, political factors (countries with over-fly restrictions), Air Traffic Control (ATC) routing, and flying out of the way to avoid or take advantage of winds aloft. Of these variables, winds aloft can be quantitatively evaluated from the reported data. In addition, differences between flight track distance traveled and direct great circle routes is evaluated.

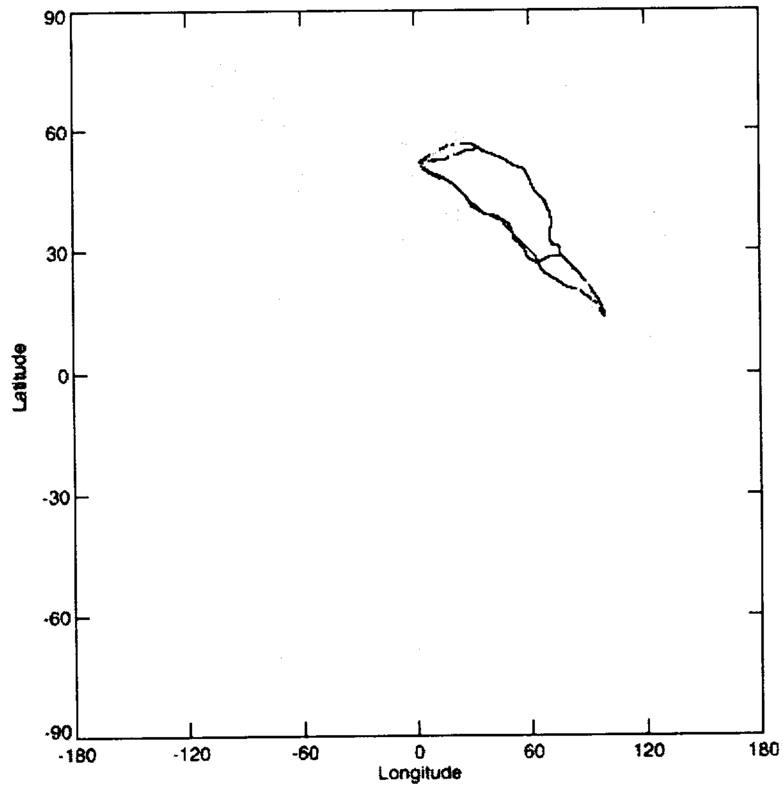


Figure 3.5. Example of an Indirect Flight Path from LHR to BKK

Figure 3.6. Flight Tracks TO and FROM LHR/JFK

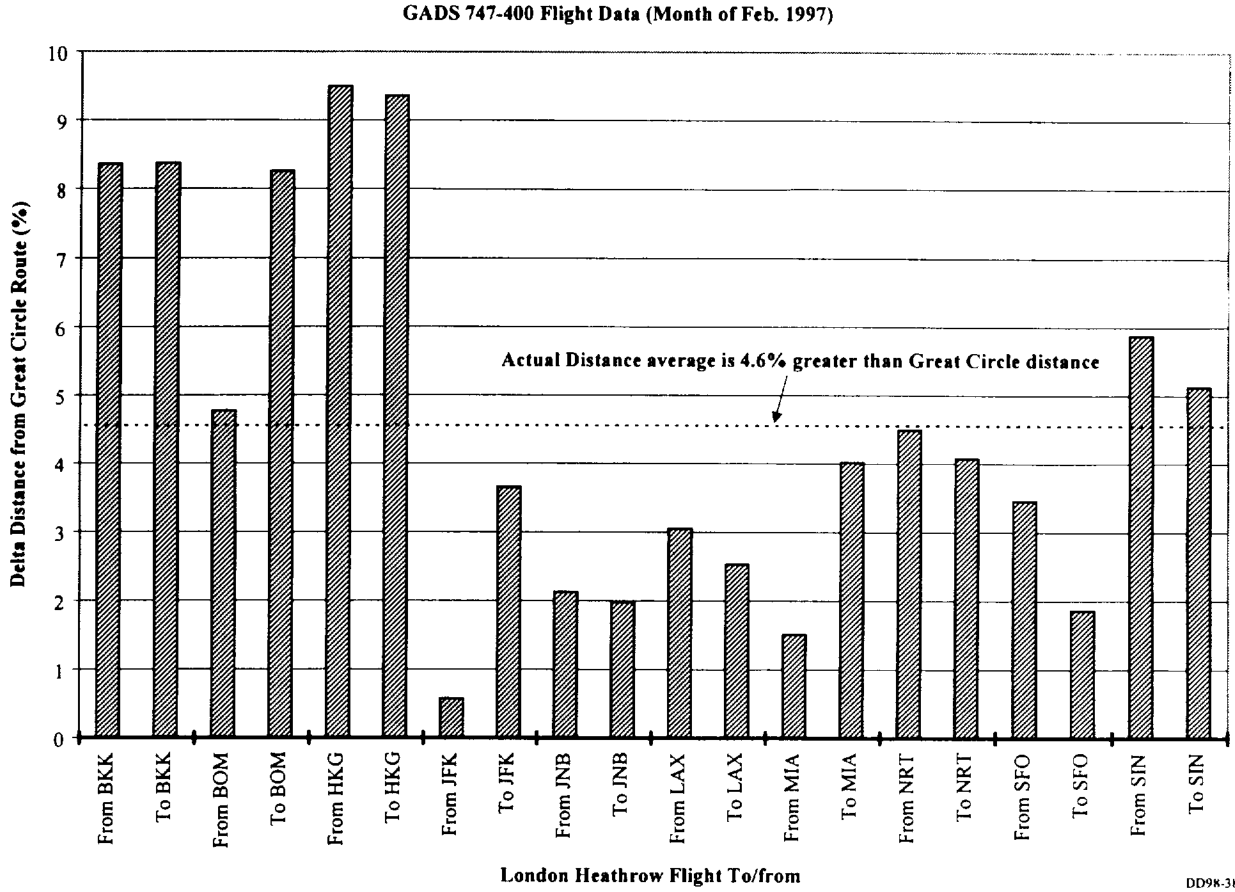


Figure 3.7. Studied Flight Distances Flown Vs. Great Circle Comparison

Figure 3.7 quantifies the increased ground track distances seen in the previous two figures by showing the increased distance that the in-service aircraft flew as compared to great circle routes. For example, Figure 3.5 shows the circuitous route flown from LHR to BKK while Figure 3.7 shows that the increased distance is 8.4% longer than the great circle distance given in Table 3.1.

JFK/LHR flights showed the highest distance deviation between the TO and FROM directions due to the separate routes required over the North Atlantic (this area uses special ATC rules to manage the very high traffic density). The routing is chosen, in part, to take maximum advantage of tail winds where possible and to minimize head winds in order to optimize fuel use.

Most of the other flights were found to follow fixed flight tracks and relied on altitude rules for traffic separation. Because of restrictions in overflying some countries, some of these flight tracks deviated significantly from great circle routes. The average increased distance traveled for all 10 city pair flights is 4.6% further than great circle distances during the cruise portion of the flight.

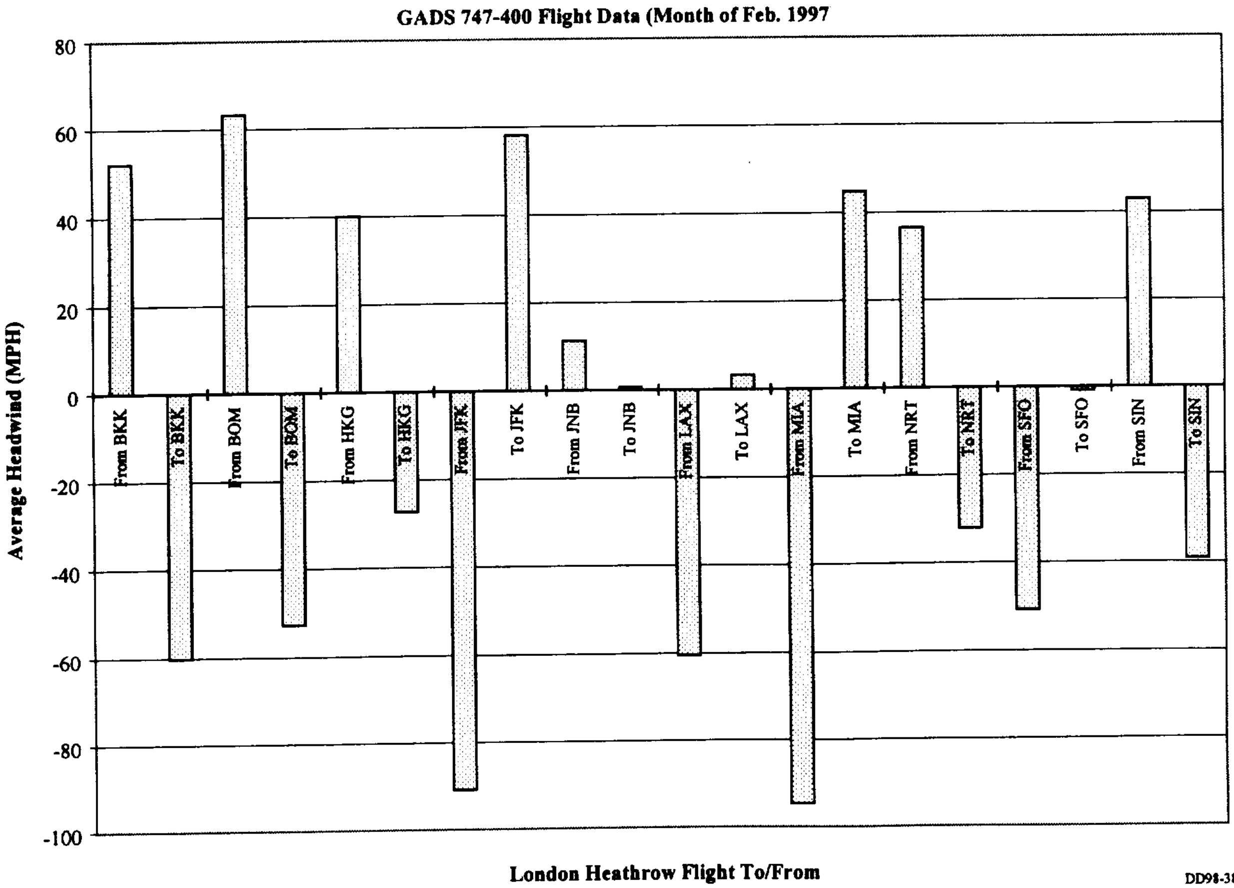


Figure 3.8. Studied Flights Average Head/Tail Winds

Figure 3.8 illustrates the average winds aloft encountered along the GADS flight paths for each of the 10 city pairs.

Flights TO or FROM BKK encounter about the same intensity of winds aloft (55-60 MPH). However, flights FROM JFK experience 91 MPH tail winds while flights TO JFK encounter an average of 58 MPH head winds. Thus, the increased distance traveled by the flights TO JFK is offset by avoiding higher head winds. As a result of aircraft taking advantage of these winds aloft, the total distance traveled over the ground may actually increase while the flight time and fuel consumed decreases. Appendix B shows the average mission head or tail-wind vectors encountered on each of the flights for the 10 city-pairs.

Figure 3.9 shows the effects of winds aloft on equivalent still air distance traveled along with a calculated reference line for 747s cruising at their Long Range Cruise (LRC) speed. The figure also provides a visual validation that the GADS winds and distance information falls within bounds of calculated values.

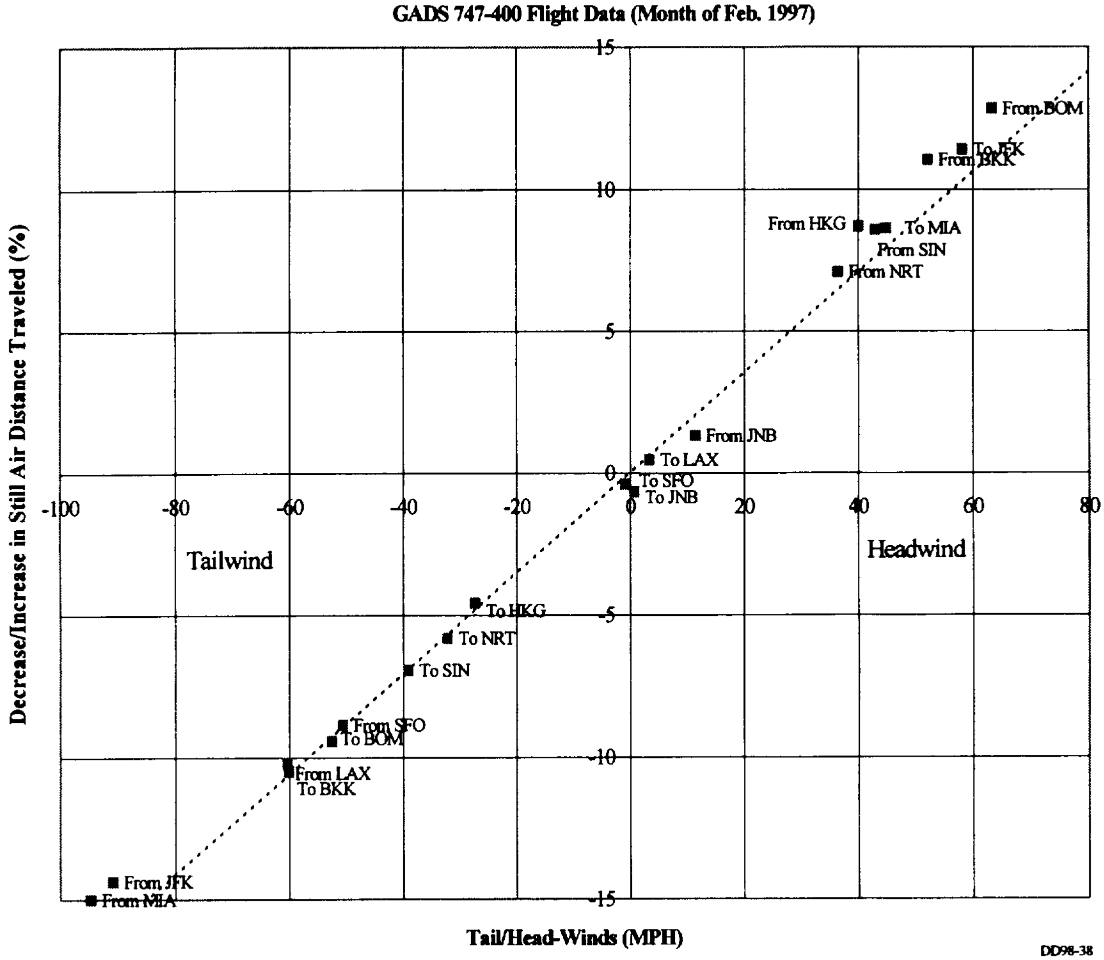


Figure 3.9. Effects of Winds Aloft on Equivalent Still Air Distance

For example, a 40 MPH head-wind will result in a 7% increase in equivalent distance (107 equivalent Vs. 100 actual miles). This equivalent distance will be referred to hereafter as "Still Air Distance" (SAD) and is referenced by the commonly used term "True Air Speed". Thus,

SAD = True Air Speed x time

or

SAD = (Ground Speed + Head Wind) x time.

Figure 3.10 graphically illustrates the Still Air Distance concept that will be used throughout the remainder of the report.

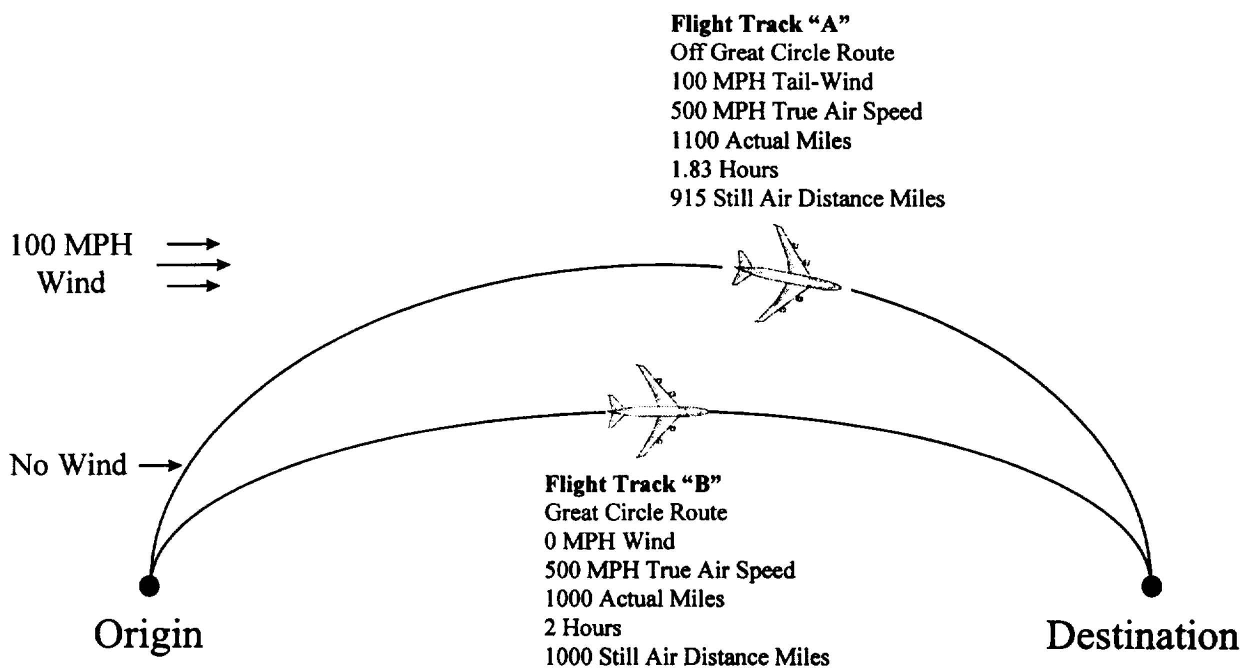


Figure 3.10. Still Air Distance Concept

Figure 3.11 shows how the still air distance varies in each direction between the 10 selected city-pairs.

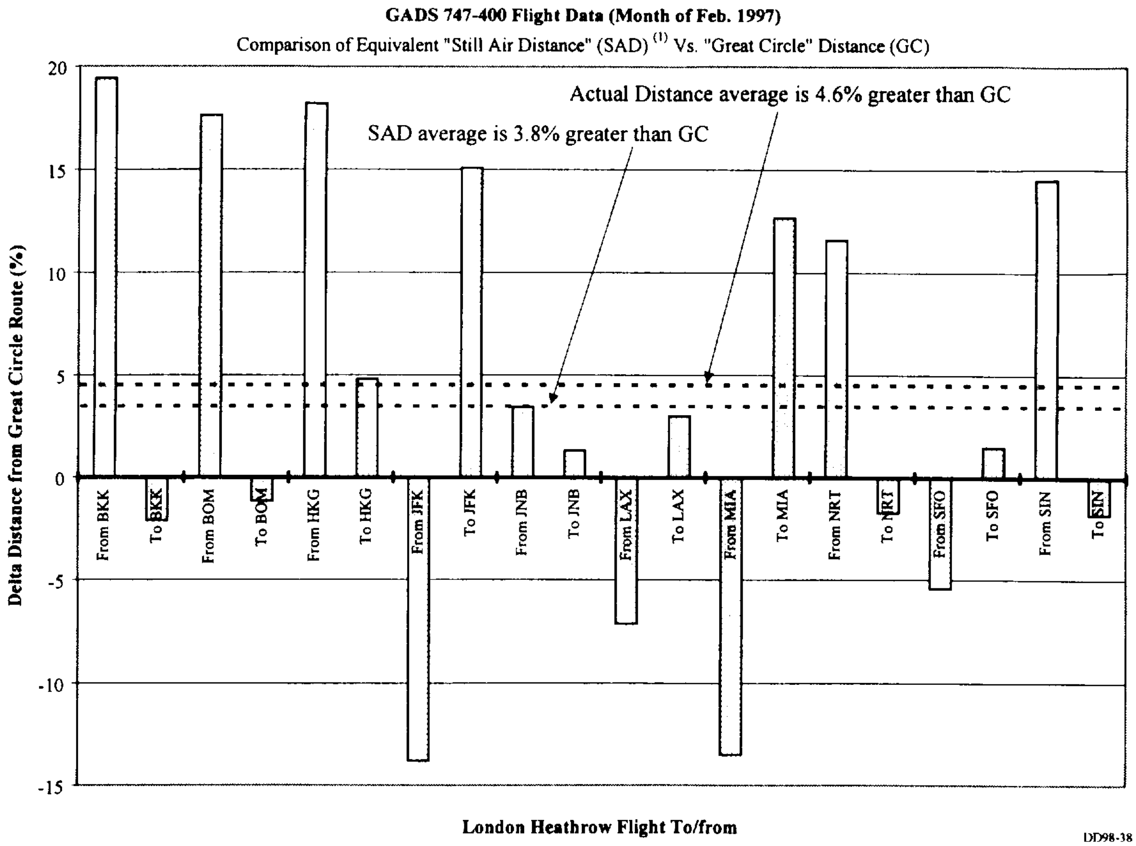


Figure 3.11. Still Air Distance Comparison

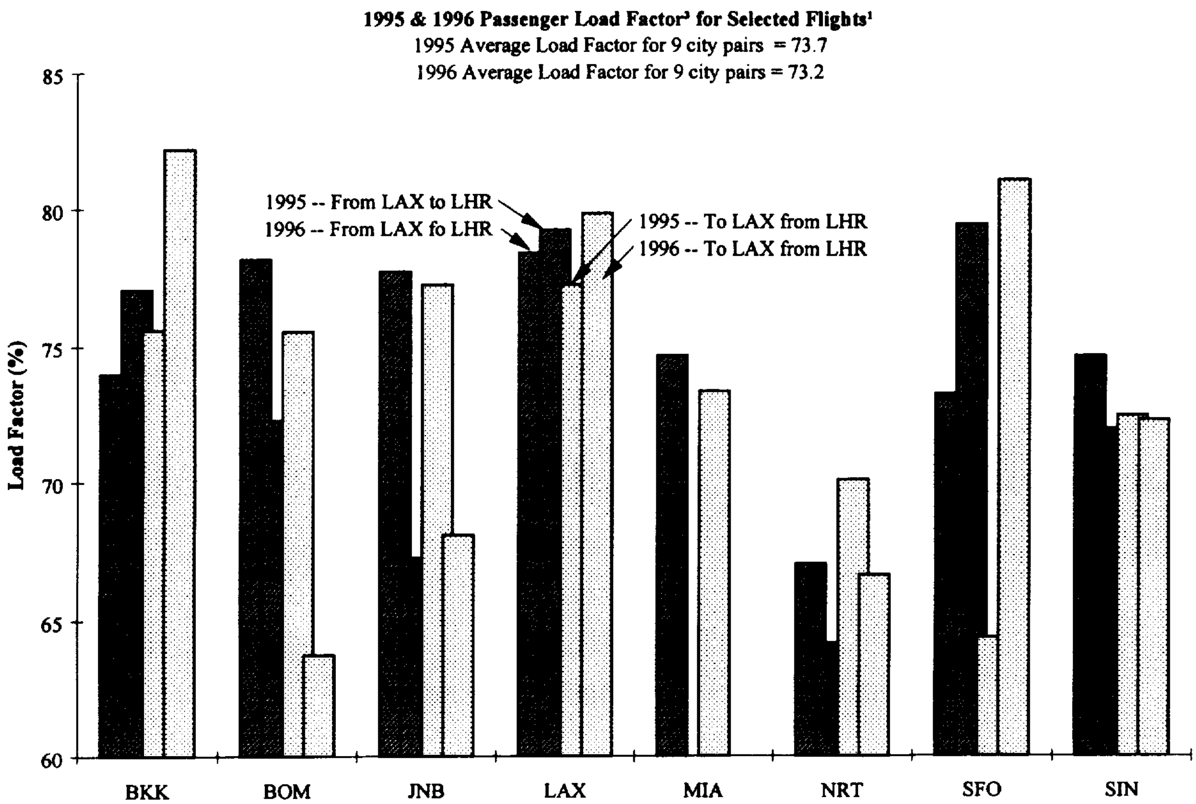
The difference between the still air distance and great circle distance in the "FROM BKK" flight is 19%. This can be attributed to an 8% increased actual distance flown (figure 3.7) coupled with an average head-wind component of 52 MPH (figure 3.8). In the opposite direction, the still air distance is 2% less than the great circle distance. These aircraft are still flying 8% farther actual distance than the great circle, but the average tail-winds of 60 MPH results in an effective decrease of 10% in distance flown, which when combined with the actual distance, results in 2% less than the great circle distance.

An important factor illustrated in Figure 3.11 is the difference between the average actual distance and the average still air distance. For all flights in the data set, not just the 10 city-pairs, the average still air distance is 0.8% less than the actual distance. This indicates that the aircraft are typically taking advantage of the winds aloft to decrease their flight time. Thus, for fuel consumption calculations, one might consider a factor to adjust for the still air distance. This factor would depend on the meteorology and direction of flight. Lastly, the studied fleet's average still air distance was 3.8% greater than the great circle distance. Appendix A provides more detail on distance traveled.

3.2.2 Aircraft Gross Weight

3.2.2.2 Load Factor & Passenger Weight Comparisons

Passenger load factor and average weight per passenger affects the aircraft gross weight. As shown in figure 3.12, the average 10 city-pair load factor for 1995 was 73.7% while 1996 was 73.2% for the sampled airline and airplane type.



Notes: 1) Data from ICAO "Traffic by Flight Stage"
2) Data for JFK, Hong Kong, & 1996 Miami not available
3) Load Factor based on standard 420 available seats for a B747-400

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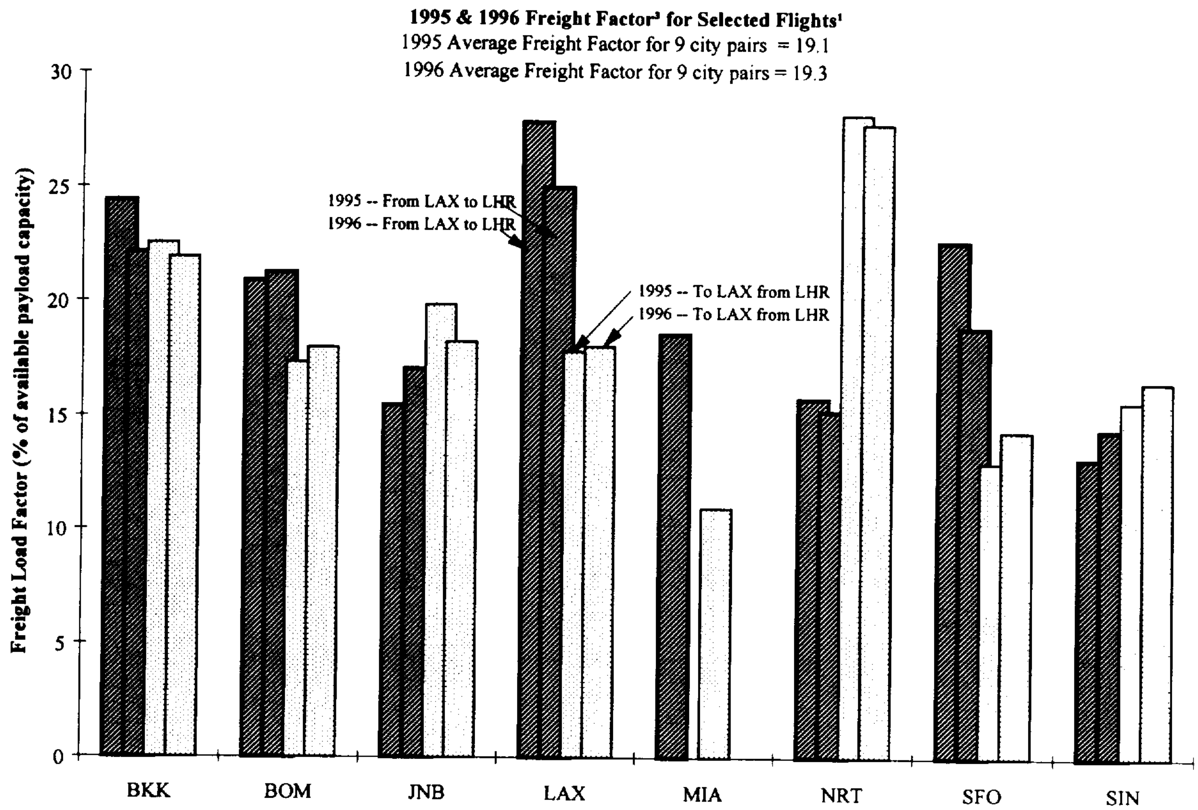
Figure 3.12. 747-400 Load Factors for the Studied Operator on 10 city-pair Flights

ICAO passenger and freight load factor data for 1997 was not available at the time of analysis. However, 1997 is believed to be similar to 1995/1996, and so 73.5% is used throughout the analysis for the operator's data.

The inventory method uses an assumed average passenger and baggage weight of 210 lb. for all flights. This operator uses an assumed average passenger weight of 233 lb. (Karl Henry, 1998, Boeing Commercial Airplane Group, Seattle, WA., personal communication).

3.2.2.3 Freight Comparison

The inventory does not include a freight allowance as part of its calculation. The actual freight carried by operators is again dependent upon airplane type, route, cargo availability and passenger load factor. As shown in figure 3.13, the ICAO freight data (ref. 6,7) lists the average freight to payload factor for the studied operator as 19.1% for 1995 and 19.3% in 1996 for the 10 selected city-pairs. As in the aforementioned passenger load factor, the two year freight factor average is used in analysis of the 1997 data.



Notes: 1) Data from ICAO "Traffic by Flight Stage"
2) Data for JFK, Hong Kong, & 1996 Miami not available
3) Freight & Mail as a percent of available payload capacity

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Figure 3.13. Freight Factors for the Studied Operator on 10 city-pair Flights

3.2.2.4 Cruise Gross Weight Comparison

Figure 3.14 illustrates the comparison between reported and calculated cruise gross weights. Due to the modeling assumptions presented in Section 1.0, the inventory 747-400s consistently show lower cruise gross weights than reported flights for the 10 studied city-pairs. The average inventory gross weight of the airplane at the beginning of cruise (29,000 ft) is 11.2% lower than that observed in the GADS information.

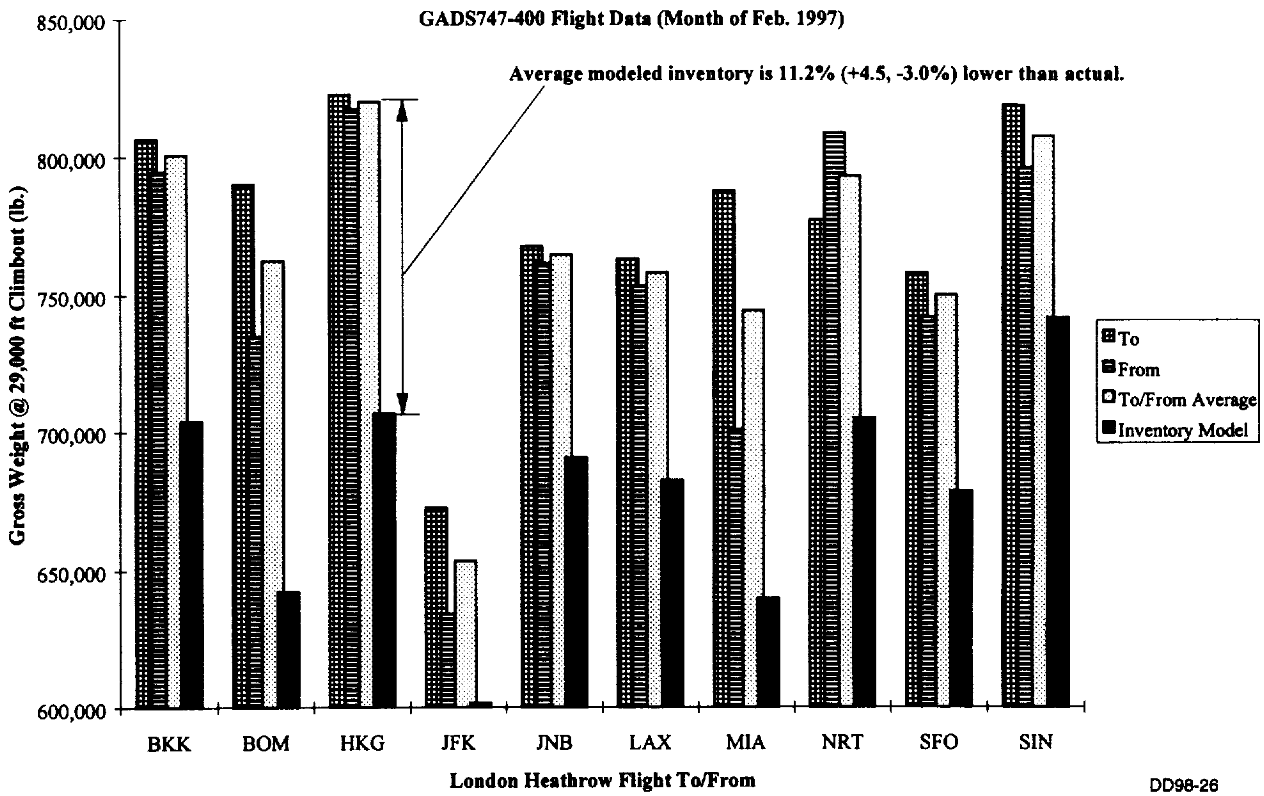


Figure 3.14. GADS & Inventory Median Cruise Gross Weight Comparisons

3.2.2.5 Aircraft Weight Gain

For each type of aircraft (e.g. 737,757,747), the operating empty weight varies between operators due to the type of engines selected (Rolls-Royce, Pratt & Whitney, or GE) and airframe options (galleys, seating configuration, etc). In addition, there is a weight growth of the airplane over time due to collection of dirt, residue and moisture. A general rule of thumb is about 1% growth for the half-life of the airframe (T. Schultz, 1998, Boeing Commercial Airplane Group, Seattle, WA, personal communication).

3.2.3 Altitude

3.2.3.1 Cruise/Climb Altitude Profile

Figure 3.15 illustrates the step-climb process for 5 LHR/JFK flights in early February versus the inventory model altitude profile.

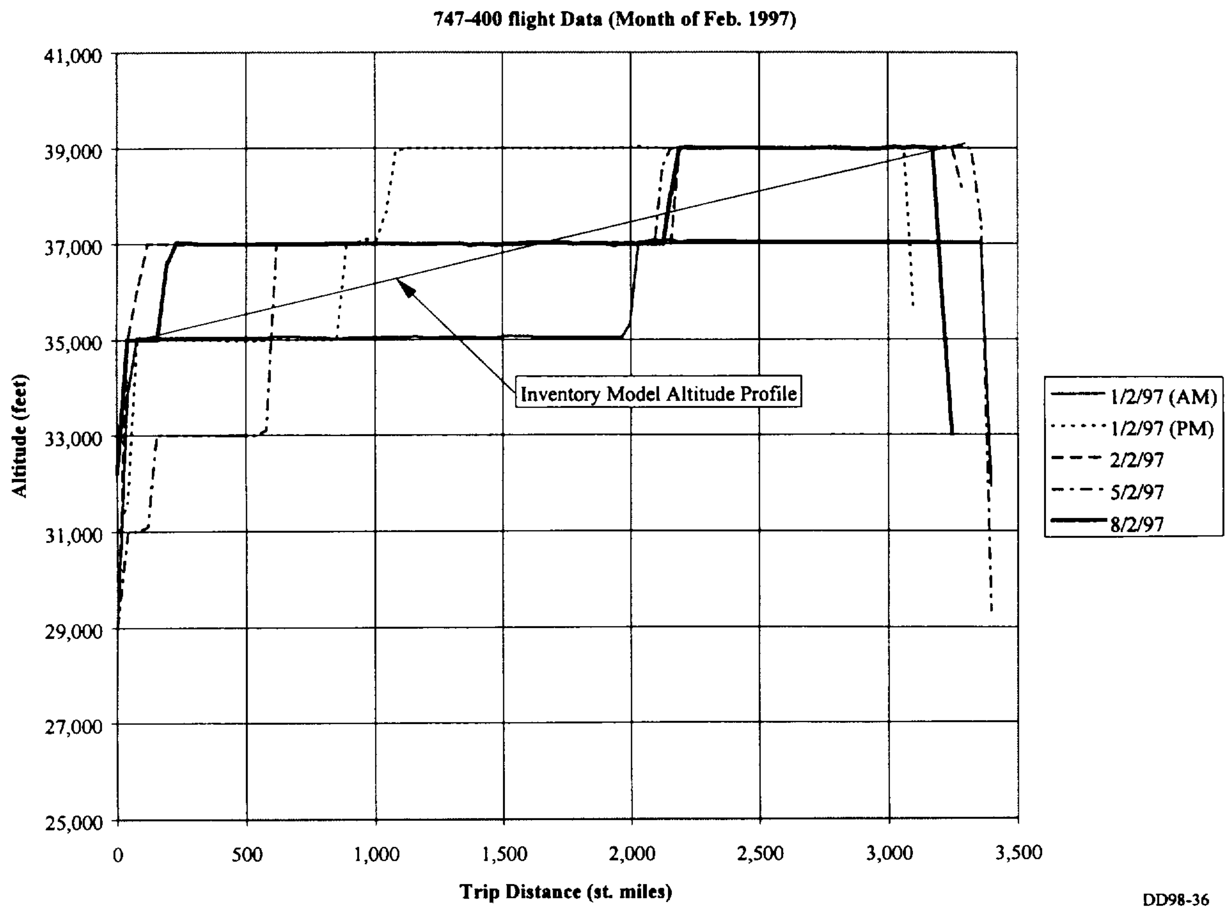


Figure 3.15. Altitude Profile for 5 LHR to JFK Flights

The inventory model calculates fuel burned based on a continuous climb cruise which has standard westbound beginning and ending cruise altitudes. For the studied carrier on this route, both profiles end at the same 39,000 foot altitude point. However, for other routes and carriers, the aircraft will not always be able to climb to their optimum cruise altitudes due to ATC and congestion constraints.

3.2.3.2 Average Cruise Altitudes

Figure 3.16 shows the average cruise altitudes for the 10 studied city pairs as well as the inventory model predicted altitude.

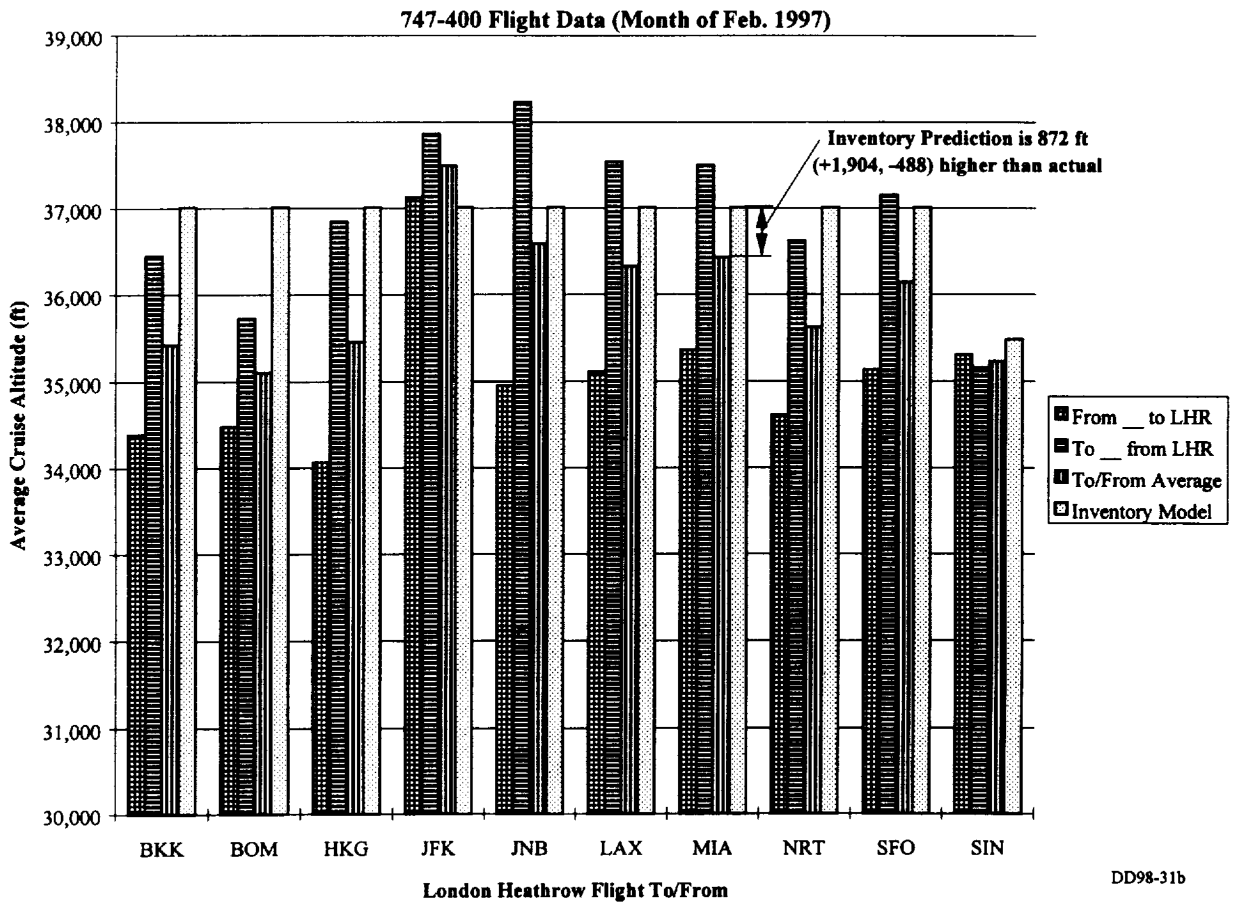


Figure 3.16. Comparison of Inventory and GADS Average Cruise Altitudes

The figure shows that, on average, the inventory method predicts an 872 foot higher cruise altitude than was actually flown (except for the short range, light weight JFK-LHR city-pair flights). This would seem to be consistent with gross weight differences, but the effect of specific ATC requirements for these flights is unknown.

Figure 3.17 is a summary distribution plot showing the averaged frequency (time) that the aircraft spends at each altitude. Appendix D provides more detailed information, grouping the data by airport city-pair and direction of flight (inbound/outbound). In the appendix data, separation by altitude TO and FROM the city-pairs becomes evident in many cases. Where separation is provided by flight track direction, such as the North Atlantic corridor, or under positive radar contact/control, ICAO altitude versus heading rules are relaxed. Other examples, such as LHR/HKG, show the result of altitude restrictions imposed by ATC in particular regions of the world.

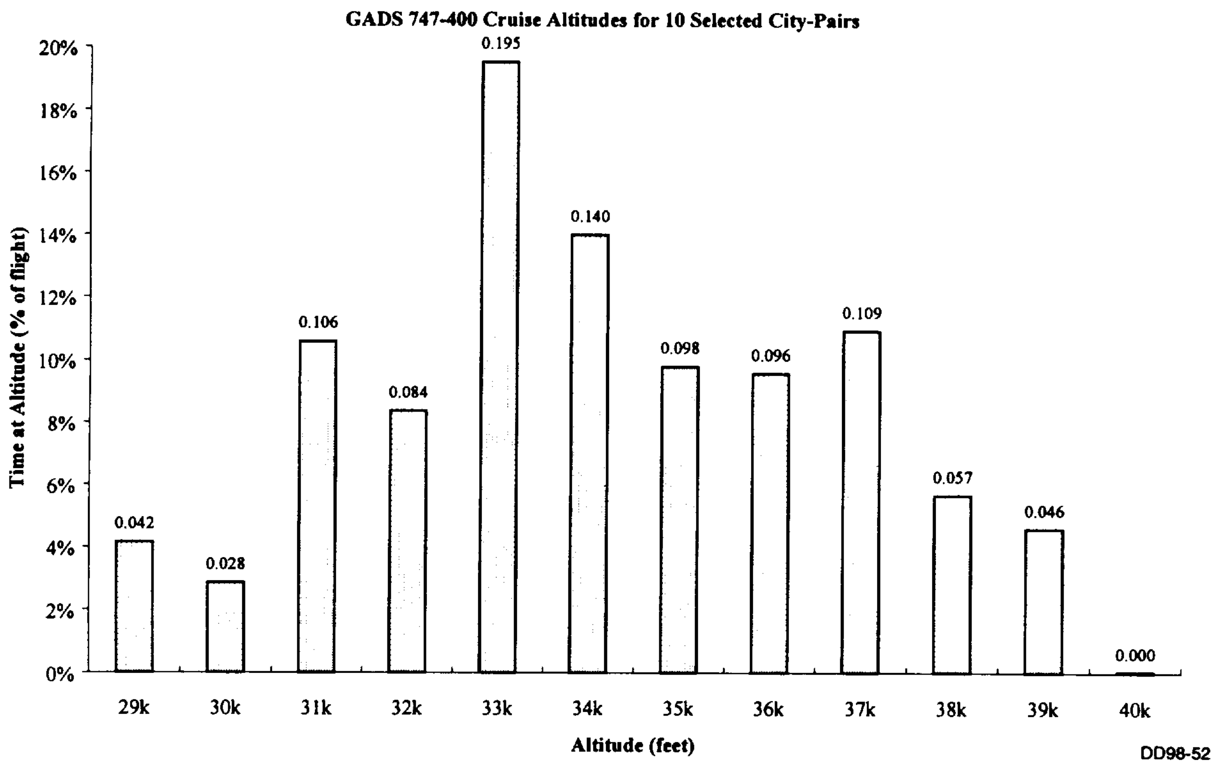


Figure 3.17. 747-400 Time at Altitude for 10 Selected City-Pairs

3.2.3.3. Optimum Altitude

Figure 3.18 shows a plot of how calculated fuel mileage changes in relation with a 747-400's gross weight and altitude.

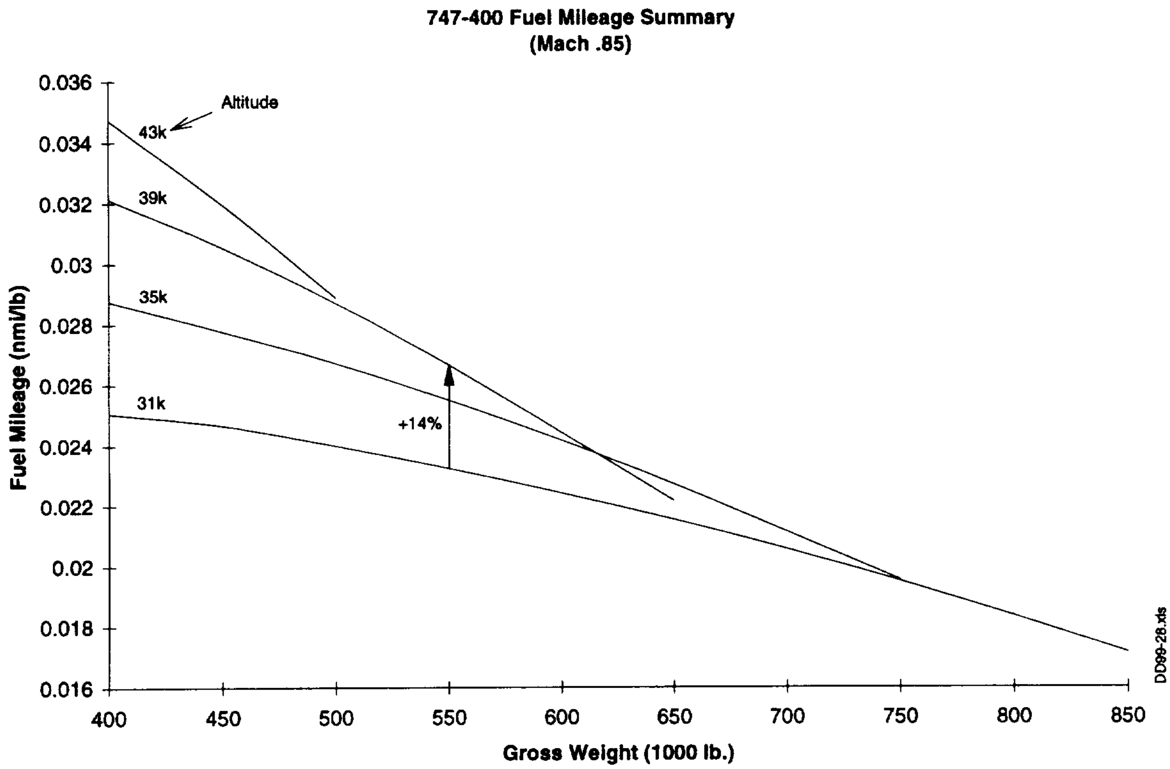


Figure 3.18. 747-400 Fuel Consumption Trends for Altitude and Weight

For any particular cruise gross weight, there is a corresponding altitude where the 747-400 will achieve its best fuel mileage, the lighter the airplane, the higher the optimum altitude will generally be. This is why airplanes should climb after using fuel and lightening their load. For example, figure 3.18 provides data showing that if an airplane did not step climb from 31,000 feet to 39,000 feet after it had burned enough fuel to reach 550,000 lb. gross weight, it would suffer a 14% fuel consumption penalty due to operation at non-optimum altitude.

Figure 3.19 shows a plot of the GADS average cruise altitude for the average cruise gross weigh of each flight. The line represents the calculated optimum cruise altitude for any given weight that will minimize fuel consumption.

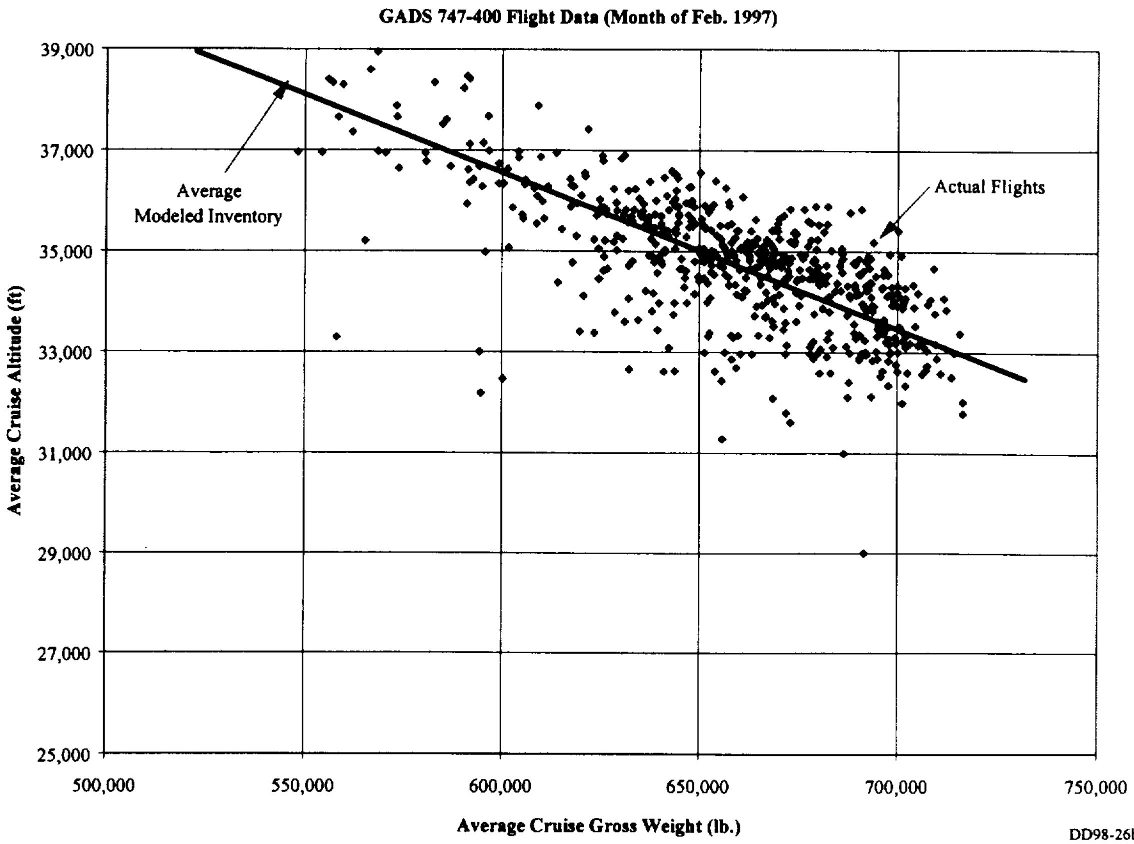


Figure 3.19. Optimum Altitude Vs. Actual Flown

The above figure illustrates that the GADS aircraft are generally flying near their optimum altitudes. Thus, little impact will expect to be seen for GADS mission fuel consumption comparisons due to operation at non-optimum altitudes.

3.2.4 Ambient Temperature

3.2.4.1 Temperature Throughout Flight

Figure 3.20 illustrates one of the most extreme temperature fluctuations experienced en route, which were for flights from Johannesburg to London.

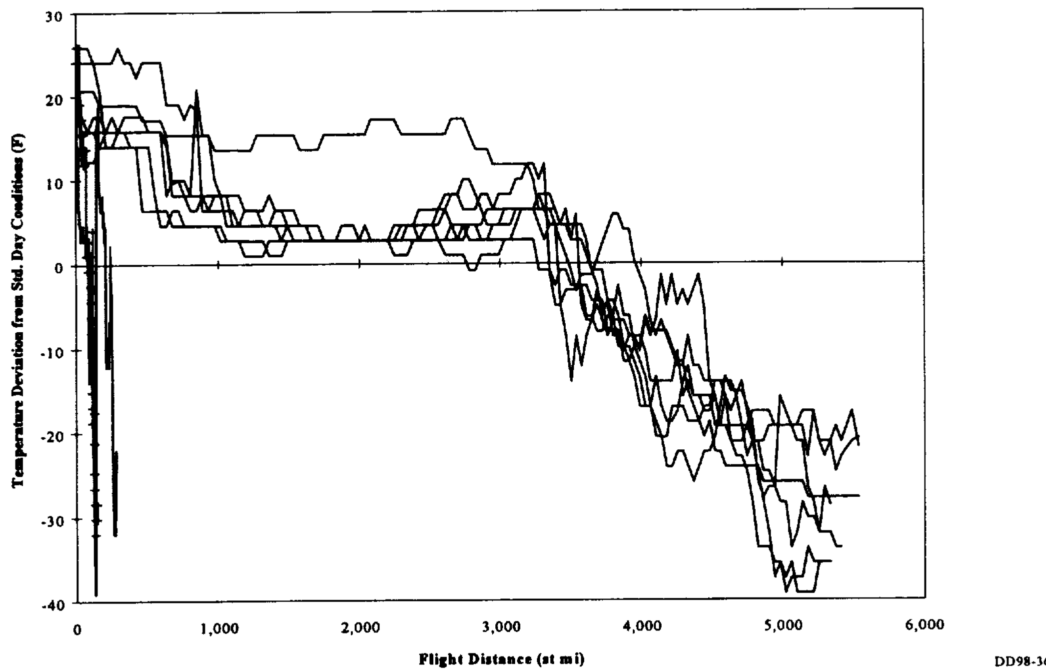


Figure 3.20. JNB/LHR Ambient Cruise Temperature Fluctuations (February 1997)

3.2.4.2 Temperature Deviations from Standard Day Conditions

The average temperature of every GADS flight during February is shown in the Figure 3.21. Except for 2 flights to NRT and 2 flights to SFO, all of the average temperatures of the 10 city-pairs fell within +/- 10 C.

3.2.4.3 Effect of Temperature Deviations on Fuel Consumption

Figure 3.22 shows the effect of non-standard temperatures on 747-400 cruise fuel mileage. As the ambient temperature increases, fuel mileage (nmi/lb) decreases. As a general rule of thumb, for every 1% increase in temperature, the engine fuel consumption rate increases ½ % (ref. 8). This, as well as airframe effects, will impact the airplane's fuel mileage and will vary between engine and airframe model. For the studied aircraft, a maximum 3.3% fuel flow deviation will occur with a 10 C deviation from standard day conditions for altitudes between 28k and 36k ft. This correction will be addressed in the fuel mileage section of the report.

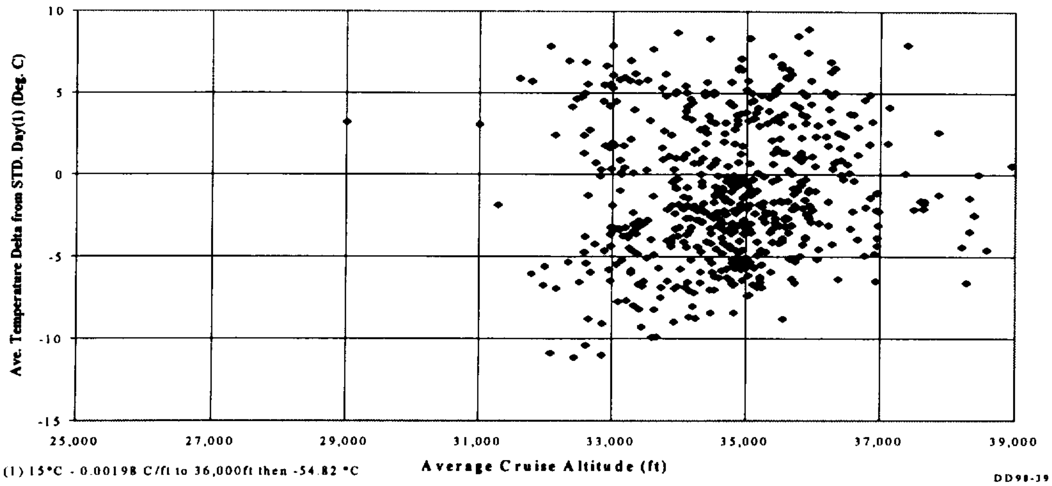


Figure 3.21. Ave. Temperature Deviation from Std. Conditions for all Feb. Flights

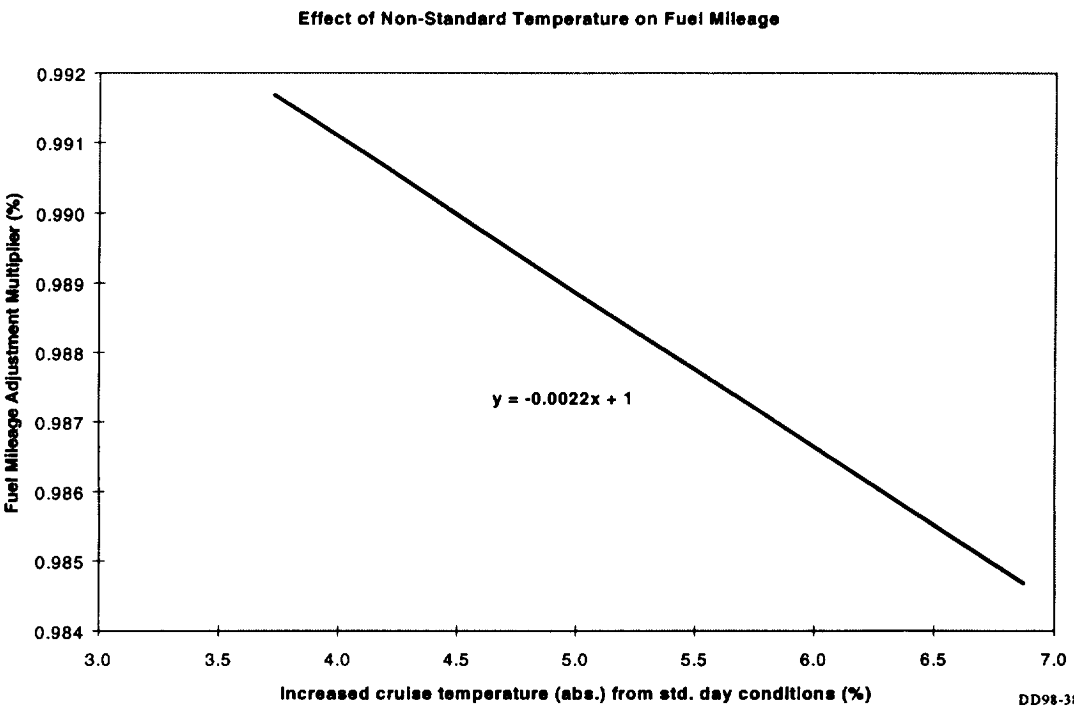


Figure 3.22. Calculated Effect of Ambient Temperature on Fuel Mileage

3.2.5 Aircraft Speed

Figure 3.23 shows the average GADS cruise speed versus weight for all 747-400 airplanes flying between 34,000 feet and 36,000 feet in February.

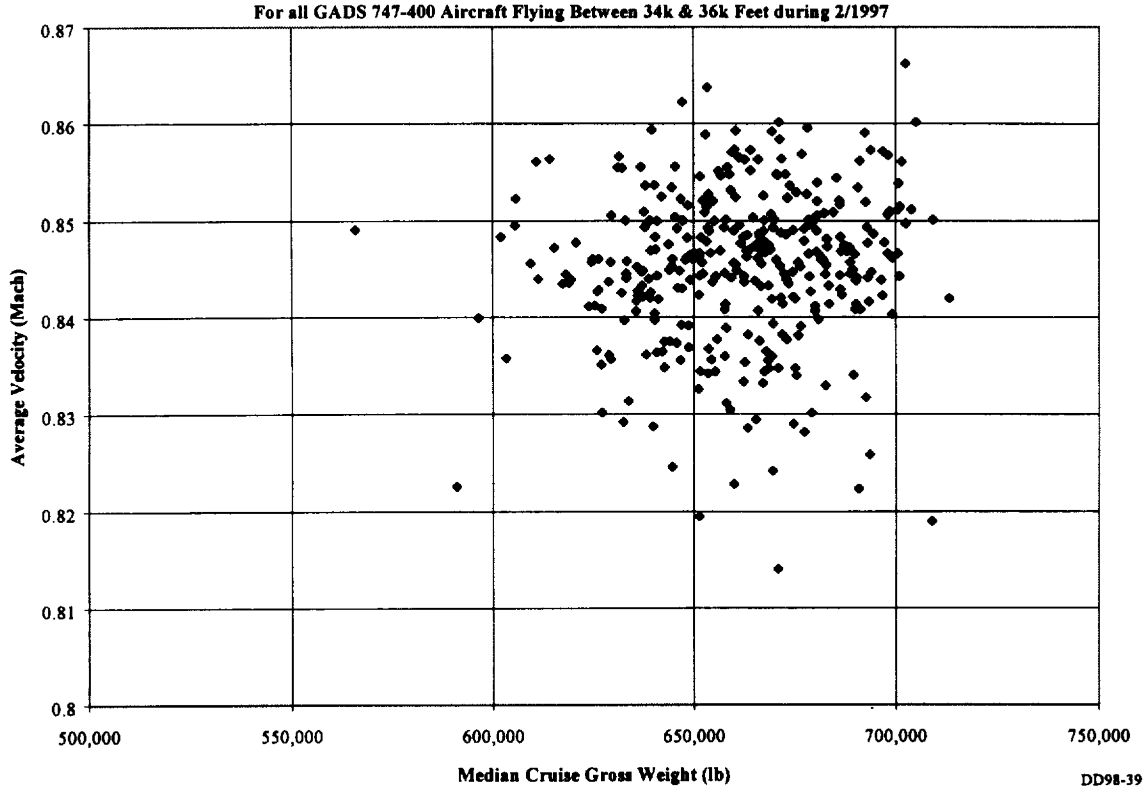


Figure 3.23. Average Cruise Speed

The 747-400 airplane's fuel consumption rate is relatively insensitive to minor speed fluctuations near its optimum *Long Range Cruise* (LRC) speed performance setting. For the majority of the cruise speeds shown above, the 747's fuel consumption rates fell around this LRC point. The operators speed setting of the airplane is consistent with the inventory calculations.

3.2.6 Fuel Mileage

The study of fuel mileage in this section is devoted solely to the cruise portion of flight. Several variables affect fuel mileage. The variables that are affected on each flight were addressed in the previous sections-- ambient atmospheric conditions (temperature and density or altitude) and aircraft operating conditions (speed and weight). The variables that change very little between the flights are addressed in this section -- engine variables (fuel energy content, efficiency) and airframe constraints (lift and drag)

3.2.6.1 Fuel Energy

There was no recording of lower heat value (LHV) for the jet fuel for these flights. However, jet fuel energy content typically is 18,568 Btu/lb. with a range of 18,435 to 18,671 Btu/lb. (ref. 9). The minimum Jet-A fuel specification requirement is 18,400 Btu/lb. The inventories assume 18,580 Btu/lb. This small variance in typical energy contents will not significantly impact the fuel mileage.

3.2.6.2 Deterioration Effects on Fuel Mileage

The deterioration of the airframe and powerplant adversely impacts fuel mileage.

Airframe deterioration results from factors that increase drag, which may be as simple as dirty wing skin panels. There was no information available for the studied operator's aircraft to assess this.

Engine deterioration leads to increases in the Thrust Specific Fuel Consumption (TSFC) due to losses in thermal and propulsive efficiency. The deterioration trends vary by manufacturer, engine model, time in service, and time since last overhaul. Again, there was no data to assess the state of the engines in the studied operator's fleet

Figure 3.24 illustrates the composite 747-400 fleet fuel mileage deterioration trend seen for 747-400 airplanes equipped with Rolls-Royce, GE and Pratt & Whitney engines (D. Hughes, 1998, Boeing Commercial Airplane Group, Seattle, WA., personal conversation based on data provided by M. Lechnar, 1994, Boeing Commercial Airplane Group, Seattle, WA., "747-400 Fuel Mileage Deterioration Trend with Service").

The GADS point marked on the chart illustrates the average age of the operator's 747-400 fleet and the deterioration level one might expect using the reported trends.

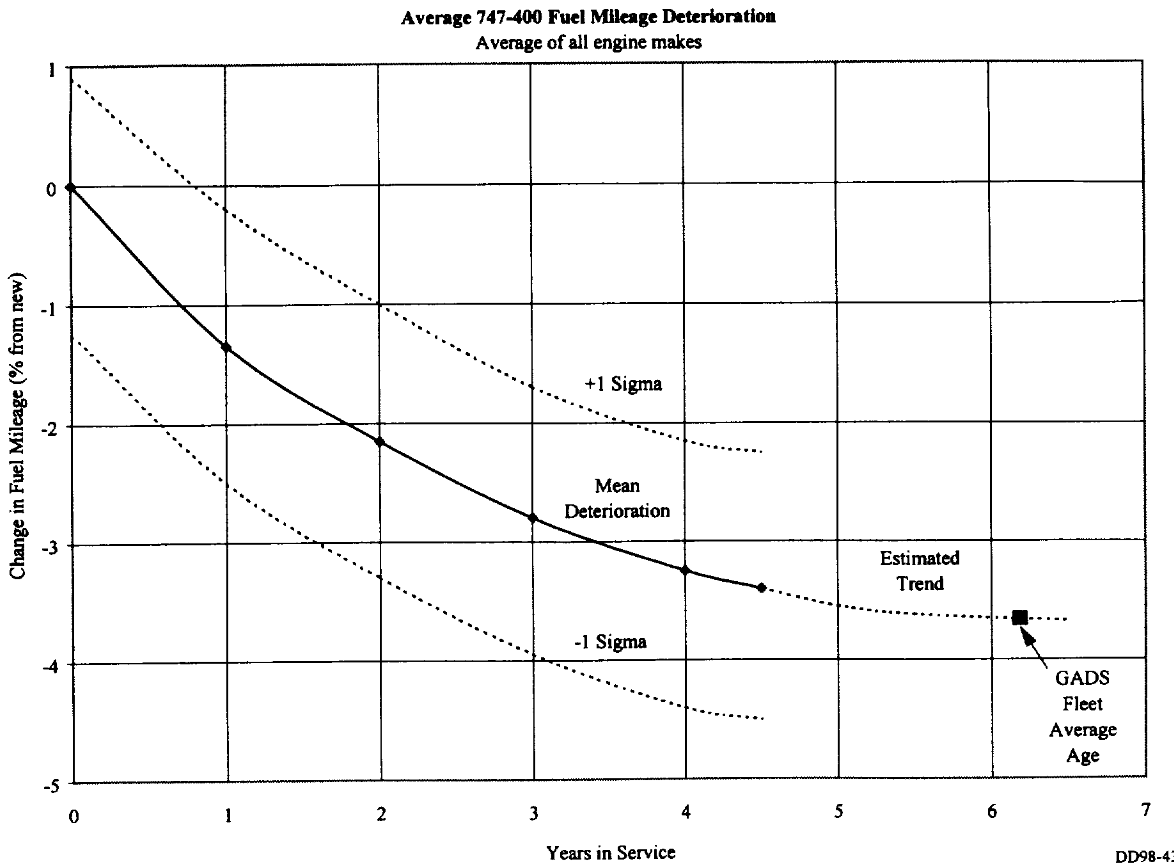


Figure 3.24. Effects of Deterioration on Fuel Mileage

3.2.7 Seasonal Variations

Following the previous analysis of the February 1997 performance data, a comparative analysis was performed using data from July, 1998 to assess the validity of the earlier data as well as to attempt to discern any seasonal variations.

3.2.7.1 February Vs. July Gross Weight

Figure 3.25 shows the mean cruise gross weight data for all flights to and from the selected city-pairs. There is little difference between the two months, indicating that the carrier is maintaining a relatively constant payload.

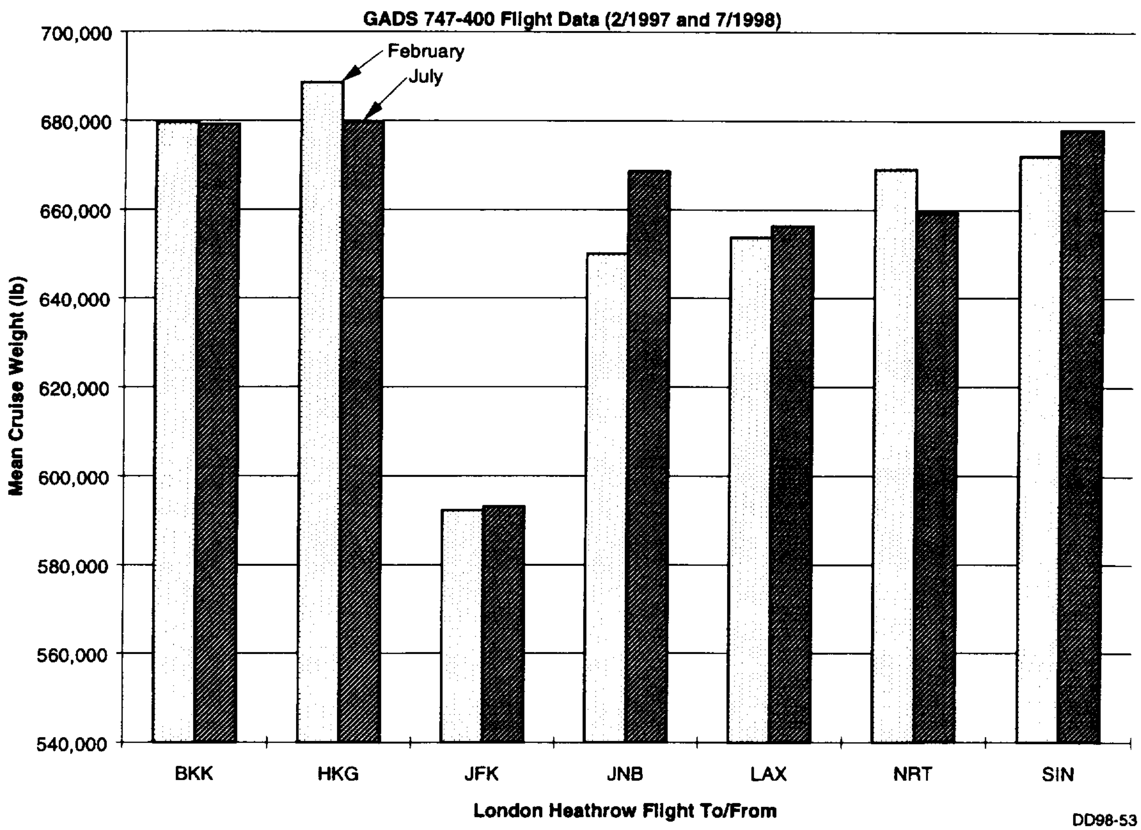
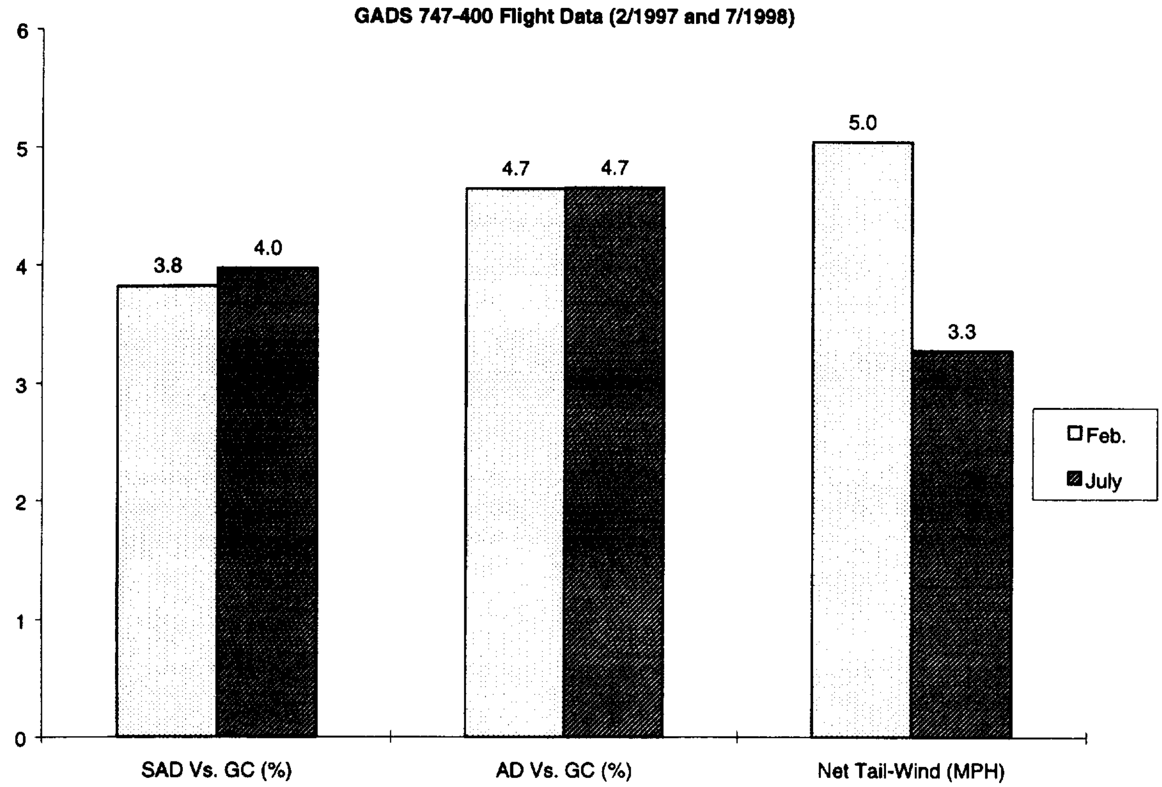


Figure 3.25 Comparison of GADS February 1997 and July 1998 Airplane Gross Weight

3.2.7.2 February Vs. July Distance Flown

Figure 3.26 illustrates the differences in distances flown for the selected city-pairs. This chart shows that the Still Air Distance increases from February's 3.8% increase relative to the shortest great circle route to July's 4.0% increase relative to the shortest great circle route. This is due to the decreased tail-winds that the aircraft see, as shown by the net 3.3 MPH tail-wind versus the net 5.1 MPH tail-winds (head-wind minus tail-wind). The chart also shows that the aircraft are flying essentially the same distance over the ground (AD Vs. GC). No attempt was made to investigate what meteorological differences exist between February and July.



NOTES: 1. AD = Actual Distance Traveled (Measured Ground Miles)
2. GC = Great Circle Route (Direct Path)
3. SAD = Still Air Distance (True Air Speed x Time)

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Figure 3.26. Comparison of February and July Travel Distance

3.3 Aircraft Data Results

Section 3.2 identified and quantified the airplane operating performance differences found between the modeled inventory and GADS records for one fleet operator using one type of airplane (747-400). This section will apply those lessons learned to a sample scenario in an attempt to establish sensitivities. In addition, this sample will help to assess some of the factors that may contribute to the differences found in section 2.0 between inventory and fleet fuel use.

We now know that the GADS aircraft have lower fuel mileage, are flying farther, and are heavier than the inventory model predicted. These variables and their impacts will now be discussed.

3.3.1 Updated Cruise Fuel Mileage

Figure 3.27 shows the fuel mileage calculated from the February GADS information for each flight's mean cruise gross weight (shown by the circles). The linear trend is shown by the heavy dashed line. As a comparison, the predicted inventory fuel mileage is also plotted for each flight after being adjusted to the same weight, altitude, temperature and speed as the actual GADS flight. These data points are shown as crosses. The thin dotted line through this data shows the trend. The difference between these trend lines amounts to around 4%. Much of this difference is probably attributed to deterioration effects.

Taking into account the aircraft's cruise gross weight, altitude, ambient temperature, speed, and projected deterioration, the average fleet fuel mileage trend line matches the actual trend line to within 0.4%. This indicates that the inventory model will accurately predict fuel mileage, given the correct input assumptions.

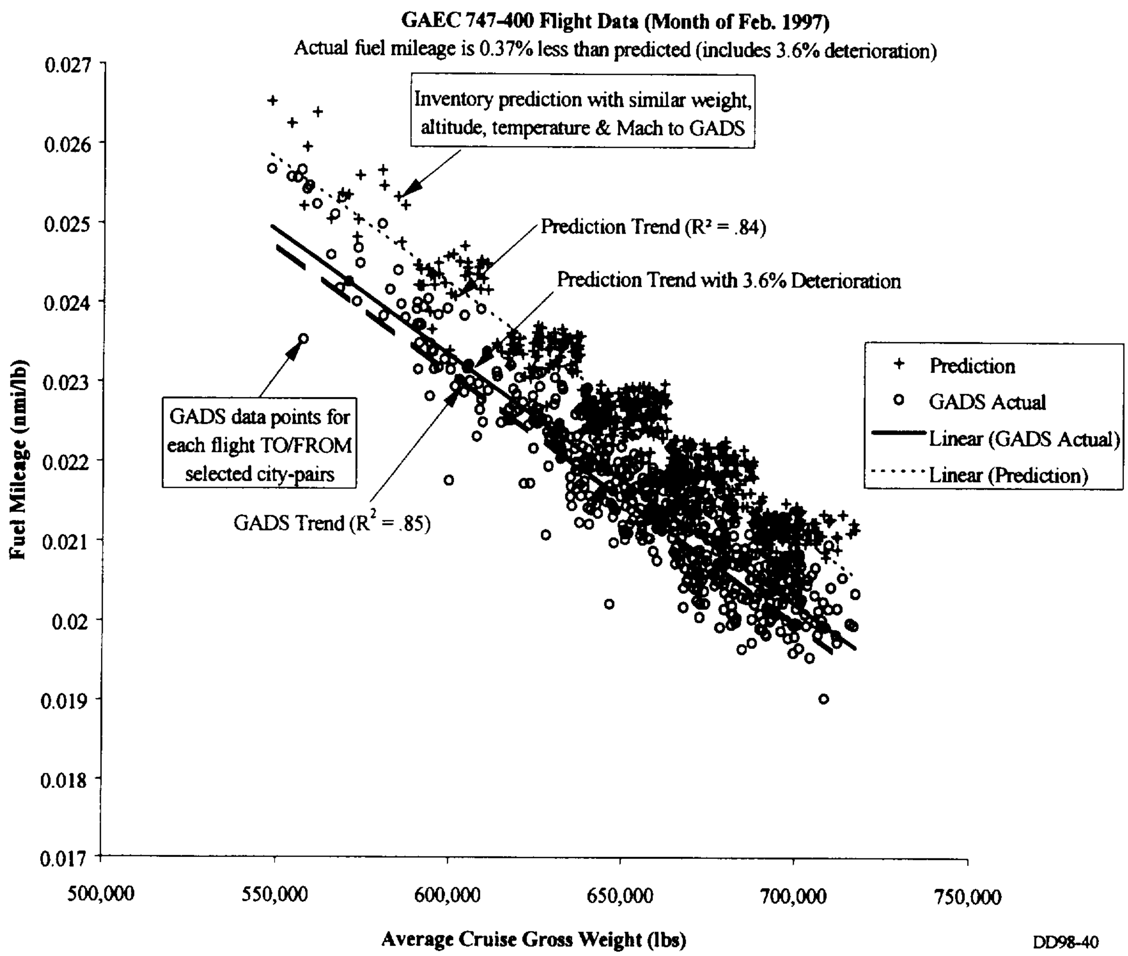

Figure 3.27. Inventory Fuel Mileage Comparison with Actual using GADS Conditions

3.3.2 Updated Cruise Gross Weight

To get a feel for the magnitude of how the variables identified in section 3.2 affect cruise gross weight, two example flights are compared . A sample 5,000 mile 747-400 flight at 70% load factor was modeled to establish a baseline. Next, using the operating characteristics from the operator's fleet just discussed, a comparison flight was modeled. The comparison flight modeling sequence is as follows:

Section 3.2.2.3 provided an insight that the typical freight carried was about 19% of the payload capacity for the particular flight. The average freight carried for all of the studied flights was 23,977 lb. for 1995 and 1996. This value is used, as shown in Figure 3.28, and represents the largest portion of airplane gross weight increase. Section 3.2.2.2 showed that passenger weight was 23 lb. per passenger higher than the baseline (233 lb. Vs. 210 lb.) At a 70% load factor, this increases the aircraft gross weight by 6,762 lb. In addition, the studied fleet's load factor was 73.5% Vs. 70%. This 3.5% load factor increase, at 233 lb/passenger, resulted in an additional 3,392 lb. of carried payload. Section 3.2.2.5 showed an airframe mid-life weight gain. Considering the average age of the operator's fleet is approximately at their quarter-life, this adds about ½% of the empty gross weight to the payload, or 1,994 lb. Section 3.2.6.2 suggests that fuel mileage will have deteriorated approximately 3.6%. It is calculated that this will require 7,995 lb. more fuel for a 5,000 mile flight. This fuel weight is added to the aircraft's gross weight. Section 3.2.1.2 showed that the studied aircraft fly 3.8% further than the most direct route. This additional 190 flown miles (at the end of the mission) is calculated to require 8,676 lb. more fuel. Finally, all of the aforementioned added weights cause the airplane's gross weight to increase. To carry these additional weights over the sample mission requires a calculated 16,730 lb. more fuel. In all, 69,526 pounds of additional weight (10.7% more than the standard inventory model), is accounted for by the variables that have been discussed. This matches very closely to the observed GADS 11.2% difference in weight that was reported in section 3.2.2.4. All of these increases are shown in Figure 3.28 along with the other, unaccounted for, weight (3,273 lb.) that would make up for the discrepancy between the studied airplane fleet's 11.2% increase (Figure 3.14) and this calculated 10.7% increase.

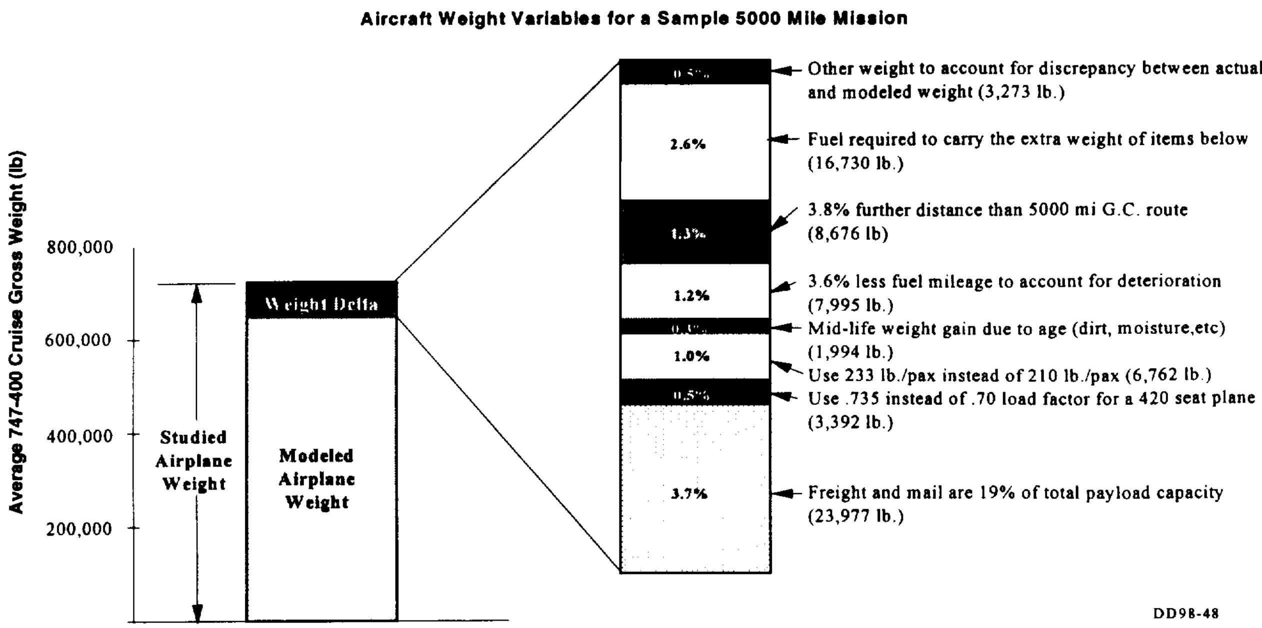

Figure 3.28. Difference in weight between GADS and a 5000 mile inventory flight

3.3.3 Updated Mission Fuel

The previous two sections showed good agreement in weight between the inventory model and actual GADS recordings, provided that similar input assumptions are made to the model. Now, modeled fuel consumption differences between two flights are compared in Figure 3.29.

The first modeled flight uses the standard inventory assumptions that were identified in section 1.0. These are: 70% LF, no cargo, 210 lb./pax, 50 hour airframe and engines, great circle distance, cruise climb, standard day conditions, and best aircraft operating points for a sample 5000 statute mile trip.

The second flight uses the GADS fleet average operating points for the 10 studied city-pairs. These are: 73.5% LF, 23,977 lb. cargo, 233 lb./pax, used aircraft (1,994 lb. weight gain & 3.6% fuel mileage deterioration) and a 3.8% increase in equivalent distance flown (5,190 total mission statute miles). Cruise climb, standard day conditions, and best operating profiles are used as defaults.

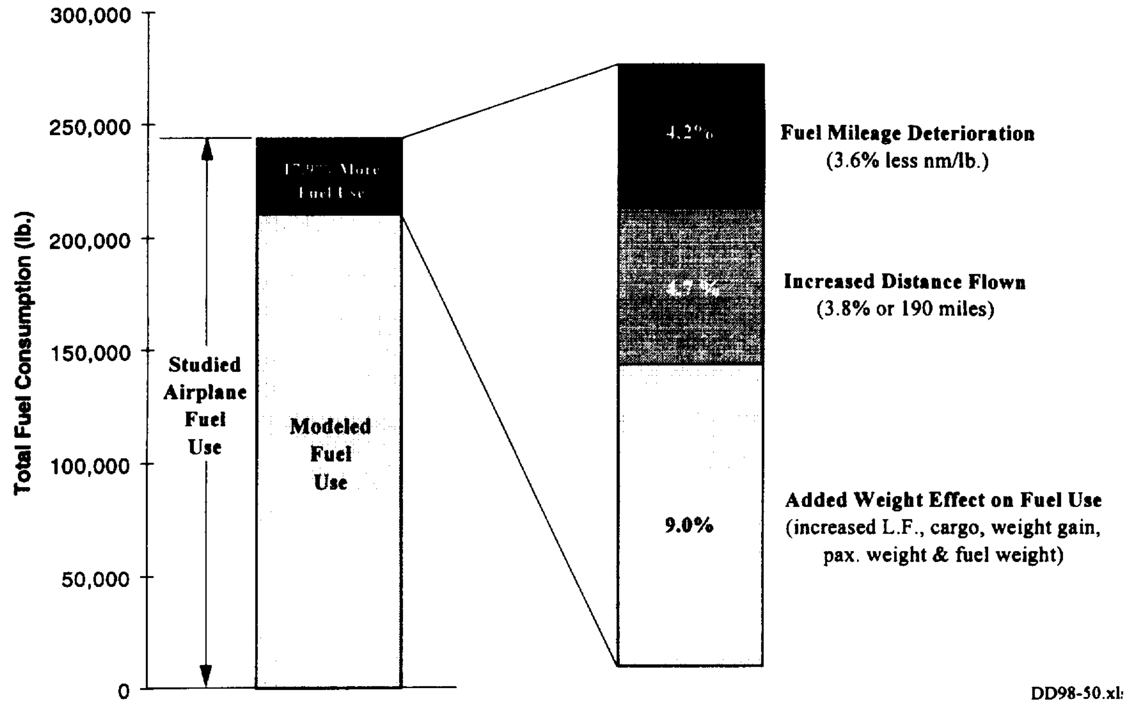

Figure 3.29. Increase in Fuel Required for a 5000 mile GADS Vs. Inventory Flight

There is a 17.9% fuel consumption increase required to fly the second scenario mission (GADS) versus the first (Inventory). The extra fuel required to carry the additional weight of cargo (45,000 lb.), increased LF, increased passenger weight, airplane weight gain, and weight of the additional fuel itself results in a 9.0% increase in mission fuel burn.

The quantity of fuel required to fly an additional 190 miles represents the average 3.8% farther distance that aircraft fly for the studied 10 city-pairs. This fuel quantity is not only the amount burned in the engines during that 190 miles, but also includes the fuel required to carry that fuel-weight for 5000 miles. Thus, the total added fuel to travel the additional distance is equivalent to a 4.7% increase in fuel burn from the baseline scenario.

Finally, due to an assumed average 3.6% airframe and engine fuel mileage deterioration rate, the additional required mission fuel is 4.2% more than the inventory baseline.

The total additional fuel required to fly the updated 5000 mile trip results in a 17.9% increase over the baseline inventory mission. This may help to explain some of the fuel use discrepancies found in section 2.0

4.0 PAYLOAD PARAMETRIC ANALYSIS

4.1 Preface

Average scheduled fleet aircraft passenger load factors have increased over time (55% in 1970, 67% in 1995, ref. 10) and are expected to increase in the future. Passenger load factors also vary from route to route, and from carrier to carrier (ref. 6,7). Aircraft also carry additional payload as freight and mail, although this aspect has not been as well characterized in the publicly available data. The NASA inventories were calculated assuming a 70% passenger load factor and no freight or mail. As more data that characterizes payload such as that presented in Section 3 becomes available and that presented in references 6 and 7 becomes more rigorously defined, the possibility of assessing the variation of aircraft payload by region and of accurately adjusting the released inventories to more closely reflect actual payloads becomes tenable. This study investigates the impact of differing payload assumptions on emissions and looks at how emissions inventory results could be adjusted to take this into account. Results of this study also give a feel for the error that can be expected in emissions calculations due to certain payload assumptions.

As a first step in developing a method for adjusting emissions inventory calculations for passenger load factor assumptions, a parametric study is presented that examines the effect of aircraft payload on CO_2 and NOx emissions. For purposes of this study, aircraft payload consists of passenger related weight (passenger and baggage) and cargo related weight (freight and mail). The concept of added payload due to tankering of fuel was examined in previous work (ref. 2) and will not be re-examined here.

4.2 Methodology

Four airplane types were studied at five different loadings to establish trends for CO_2 and NOx emissions as a function of payload. The airplane types studied are listed in Table 4.1 along with aircraft weight information and details regarding assumptions made about passenger weight and seating. The loadings considered in this study were 50%, 70% and 100% passenger load factor (no freight or mail) and 75% and 100% maximum structural load.

For each aircraft type and loading, the total CO_2 and NOx produced over individual flights of various lengths within the design range of the aircraft were calculated. Detailed performance calculations were used to obtain mission fuel burn from which CO_2 was directly calculated. Boeing Method 2 (ref. 2) was used to calculate mission NOx from airplane performance data and ICAO engine emissions data.

An assessment was also made of the effect of passenger load factor on the global totals of emissions and their distribution in the atmosphere for a 747-400 aircraft run on multiple flights between multiple city pairs. Flights for the 747-

400/PW4056 aircraft/engine combination were selected out of the May 1992 flight schedule that was originally used to create the NASA 1992 scheduled aircraft fleet global emissions inventory. For these selected flights, global emissions of NOx were calculated on a 1 degree latitude by 1 degree longitude by 1 kilometer altitude grid with 70% and 100% load factors utilizing the method used to calculate past NASA global emissions inventories (ref. 1,2). Global totals of NOx and CO_2 for the two loading conditions were calculated and compared. An altitude distribution of the change in global NOx created by increasing the load factor from 70% to 100% was also generated.

Table 4.1. Aircraft Types Considered in the Parametric Load Factor Study

Aircraft	Engine	PAX Weight (with baggage, lbs.)	# PAX (100% LF)
747-400	PW4056	210	420
777-200	PW4084	210	305
757-200	PW2040	200	194
737-700	CFM56-7B20	200	128

4.3 Results and Discussion

Figures 4.1 through 4.4 show the results of single mission NOx and CO_2 calculations made for different aircraft loadings for the four aircraft considered in this study. In these plots, aircraft loading is expressed as percent of the maximum payload weight that the structure of the aircraft is capable of carrying. Results of NOx and CO_2 calculations are given in terms of percentage change from the 70% passenger load factor, no cargo case which was chosen as the baseline for this study. No data for the 100% maximum structural load case is shown for the 737-700 in Figure 4.4 for the 1313 nmi range because the 737-700 is not capable of flying this mission while carrying 100% maximum structural load.

The symbols on the plots in Figures 4.1 through 4.4 represent actual calculation results and the lines represent linear curve fits to the data. Lines showing 50%, 70% and 100% passenger loading for each aircraft are included on each plot for reference.

The general trend of the data in Figures 4.1 through 4.4 is for a given mission length, aircraft carrying more payload produce more CO_2 and NOx over the mission. The data also suggests that different airframes may have different sensitivities to payload as far as CO_2 and NOx production over a mission are concerned.

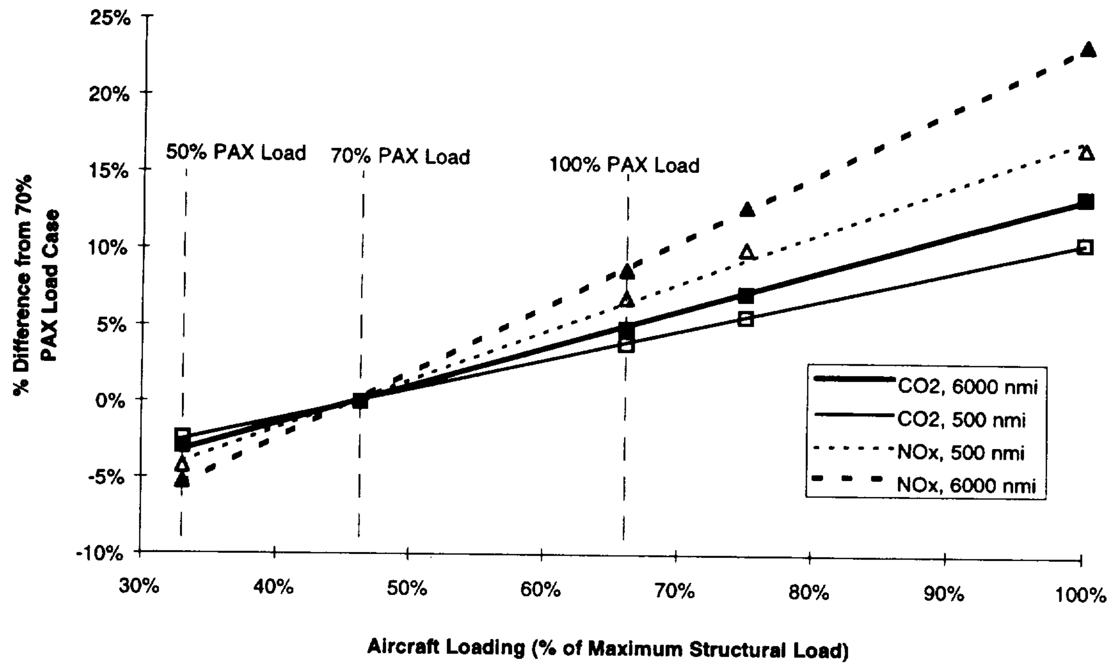

Figure 4.1. Effect of Aircraft Loading on Mission NOx and CO_2 for the 747-400

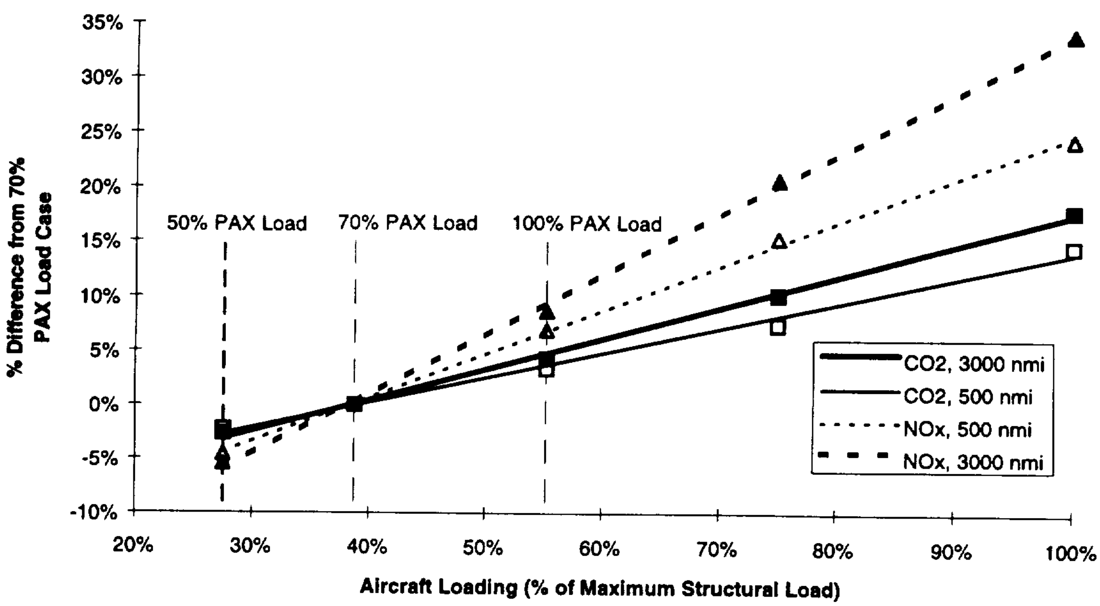

Figure 4.2. Effect of Aircraft Loading on Mission NOx and CO_2 for the 777-200

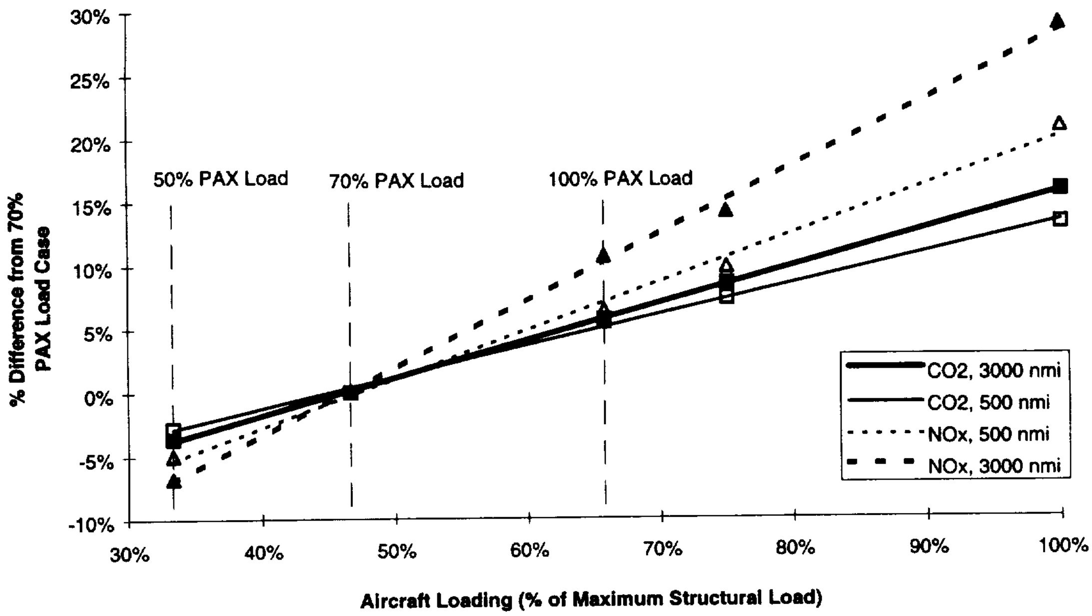

Figure 4.3. Effect of Aircraft Loading on Mission NOx and CO_2 for the 757-200

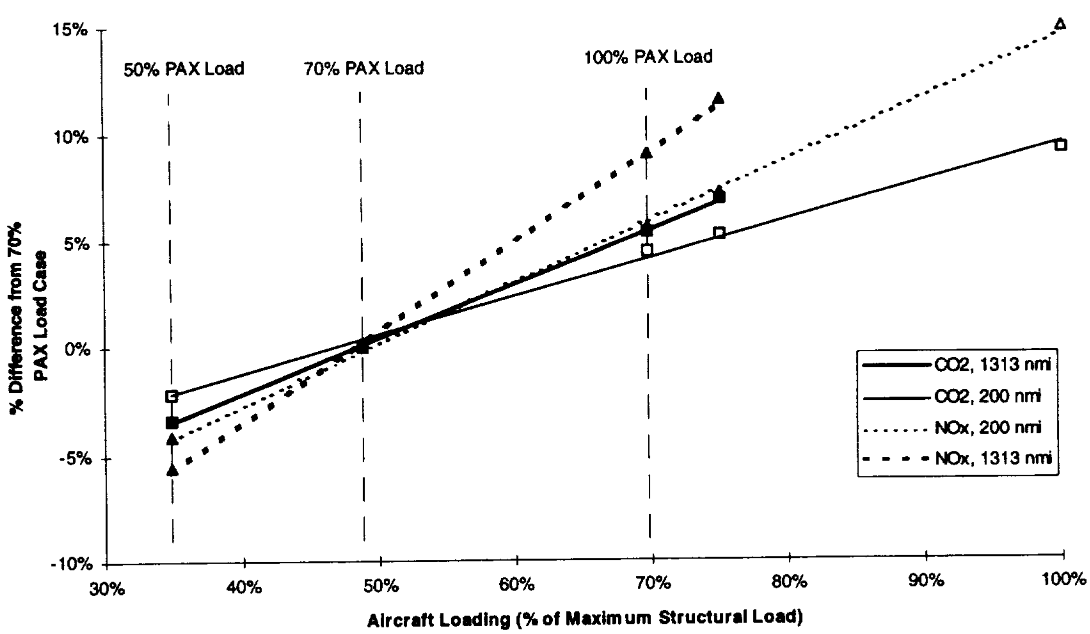

Figure 4.4. Effect of Aircraft Loading on Mission NOx and CO_2 for the 737-700

Comparing the data for the 747-400 and the 737-700 shows that the 747-400 has the potential for a greater percentage increase in emissions due to payload increases. This highlights the possibility that, although the percent error associated with calculations of emissions for two different airframes may be close to the same, the causes for the errors may be different. In the case of a large airplane like the 747, a majority of the errors in emissions calculations may be due to payload assumptions while for smaller aircraft like the 737, the majority of errors may be due to assumptions regarding factors such as air traffic control.

Table 4.2 shows the global totals of NOx and CO_2 calculated for the 747-400/PW4056 aircraft/engine combination run on the May 1992 inventory flight schedule for 70% and 100% passenger load factor with no cargo. Global totals are shown for emissions deposited over the full flight envelope (0-13 km) and for emissions deposited during the cruise portion of flights (9-13 km). The table also gives percentage differences in NOx and CO_2 totals between the two loading cases.

Table 4.2. Load Factor Effects on May 1992 Global Totals for NOx and CO_2 for a 747-400/PW4056 Run on the NASA May 1992 Emissions Inventory Schedule

Passenger Load Factor	Global CO_2 (Kg/day)		Global NOx (Kg/day)	
	0-13 km	9-13 km	0-13 km	9-13 km
70%	1.35E+07	1.22E+07	6.48E+04	5.59E+04
100%	1.41E+07	1.27E+07	7.01E+04	6.06E+04
Percent Difference	**4.4%**	**4.1%**	**8.2%**	**8.4%**

The average mission range for the 747-400 with PW4056 engines in the 1992 scheduled emissions inventory was 3,360 nmi. Interpolating the data plotted in Figure 4.1 for 100% passenger loading shows that an 8.3% increase in NOx would be expected when increasing passenger load factor from 70% to 100% for a 3,360 nmi mission. This percentage increase for the single mission case matches very closely with the percentage increase shown for the 0-13 km band in Table 4.2. It appears from this agreement that adjustment factors derived from single mission data may be useful in adjusting global emissions totals from aircraft emissions inventory calculations to account for different aircraft loadings.

The plots in Figures 4.1 through 4.4 show that the change in CO_2 and NOx produced during a single mission from the baseline case for a given loading depends on both the range of the mission and the particular airplane type. This dependence is more pronounced for NOx than it is for CO_2. Because of the dependence of the results on aircraft type and mission range, for the greatest accuracy, adjustment factors would have to be developed for each particular aircraft/engine combination in the inventory for the average mission range flown by the aircraft in the inventory. It is possible that approximate adjustments to inventory totals could be made for particular classes of aircraft having similar relationships between emissions and aircraft loading. More work would have to be done to investigate this approach.

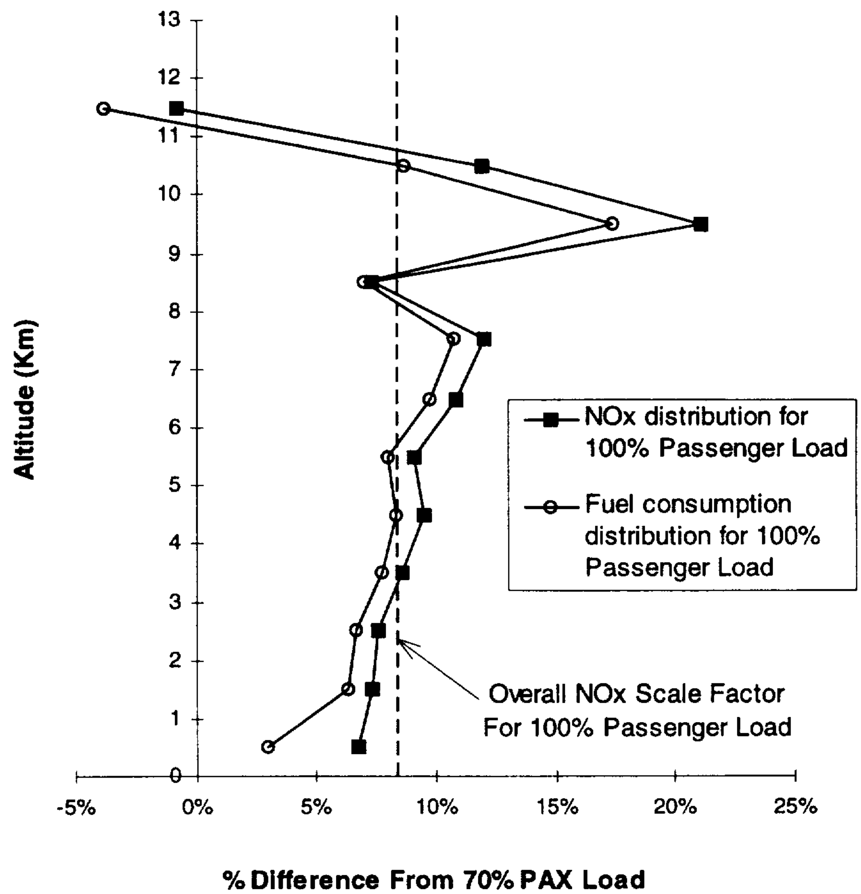

Figure 4.5. Altitude Band Distribution of Fuel Consumption and NOx for the 747-400/PW4056 run on the May 1992 flight schedule with 100% Passenger Loading Given Relative to the 70% Passenger Loading Case

Data such as those shown in Figures 4.1 through 4.4 may be useful in adjusting emissions inventory global totals. However, using such information to adjust emissions inventory calculation results on a cell by cell basis may lead to significant errors in the distribution of emissions throughout the atmosphere.

Figure 4.5 shows altitude distributions of NOx and fuel consumption calculated for a 747-400/PW4056 with 100% passenger loading (no cargo) run on the NASA scheduled inventory May 1992 flight schedule. The altitude distributions are given in terms of the percent difference from the 70% passenger load, no cargo case. The single mission average 8.3% increase in NOx relative to the 70% load factor case calculated by use of Figure 4.1 data is shown as a dotted line on this plot.

From Figure 4.5 it can be seen that if the single mission average 8.3% increase in NOx determined from single mission data were used to adjust fleet emissions on a cell by cell basis, a misleading altitude distribution of NOx for the fleet would be created. For instance, in the 9 to 10 km altitude band, an 8.3 % increase in NOx would be assumed when actual calculations show that the increase would be 21%.

The fuel consumption and NOx emissions distributions given in Figure 4.5 indicate that the 747-400/PW4056 fleet NOx emissions distribution in the atmosphere for the 100% passenger load case is shifted to lower altitudes than for the 70% passenger load case. This shift is due to the way in which aircraft gross weight impacts cruise altitude capability. Heavier gross weight aircraft will tend toward lower initial and final cruise altitudes and therefore, for the 100% passenger load case, a greater proportion of fuel is consumed at lower altitudes than for the 70% passenger load case. Because a greater portion of the fuel is consumed at lower altitudes, more of the total NOx is created at lower altitudes. For a further discussion of the effect of aircraft weight on cruise altitude, see Section 3.2.3.

Most of the increase in NOx between the 100% passenger load case and the 70% passenger load case is due to the larger amount of fuel that must be consumed in order to carry a greater payload. If the EI_{NOx} between the 70% and 100% passenger load cases remained constant, then over each altitude band the percentage increase in NOx would be equal to the percentage increase in fuel consumed. From Figure 4.5 it can be seen that this is not the case. The NOx profile is shifted slightly to the right relative to the fuel consumption profile shown on the plot. This shift is due to the fact that, as can be seen in Figure 4.6, at the higher throttle settings required to carry a larger payload, the EI_{NOx} is increased slightly. This increase is greatest during the take-off (0-1 km band) and cruise (9-13 km band) phases of flight.

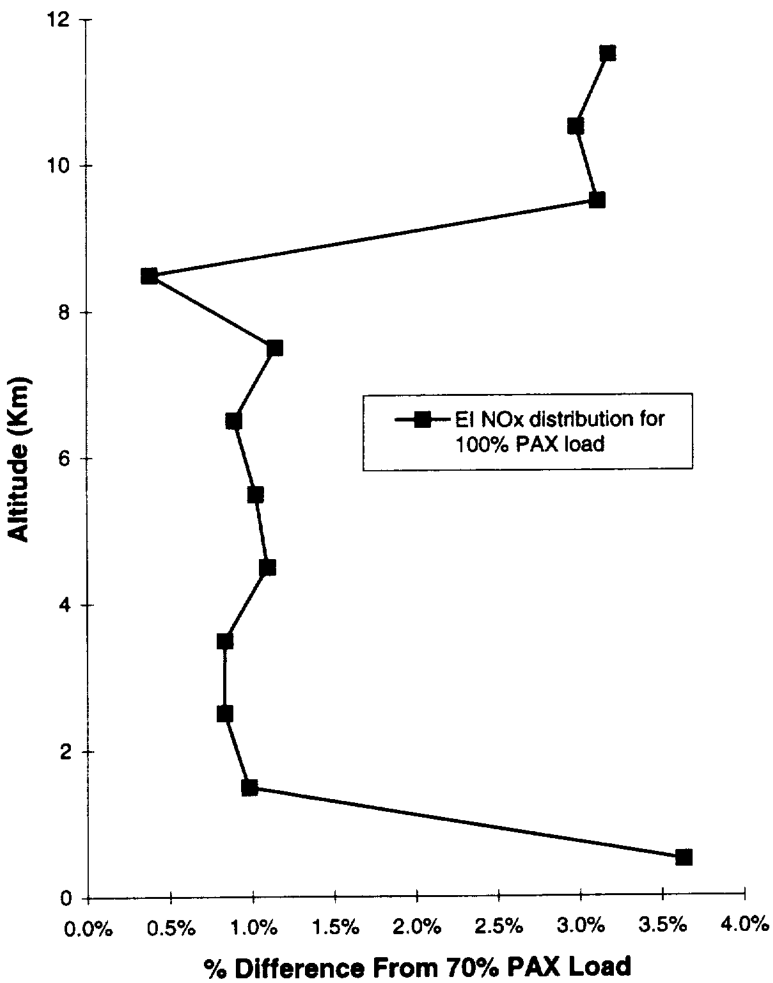

Figure 4.6. Altitude Band Distribution of EI_{NOx} for the 747-400/PW4056 run on the May 1992 flight schedule with 100% Passenger Loading Given Relative to the 70% Passenger Loading Case

4.4 Payload Parametric Study Findings

For each of the four aircraft/engine combinations studied, total NOx and CO_2 created on a single mission varied linearly with the payload carried by the aircraft. Factors for scaling CO_2 and NOx for different aircraft loadings created using single mission data for a given aircraft may be useful in scaling global totals of these emittants for that aircraft. Caution must be used when applying these scale factors on a cell by cell basis to three dimensional global emissions inventory results because incorrect spatial distribution of global emissions may result.

5.0 CONCLUSIONS

In conclusion, the three studies presented in this report showed that actual commercial aircraft fleet fuel use is higher than that modeled in inventory calculations, the inventory model will accurately predict fuel use when configured with the same operating parameters as the fleet, and that it may be possible for *total* global emissions results to be adjusted for differing payloads by the use of scale factors.

For the ten major passenger air carriers considered in the analysis done in Section 2, there was good agreement between the DOT Form 41 data and values calculated as part of the NASA 1992 scheduled inventory for total aircraft departures and miles flown. This increases confidence in the assumption that the OAG derived flight schedule used to create the NASA 1992 scheduled emissions inventory gives an accurate accounting of passenger flights that actually took place. Total fuel consumption calculated as part of the NASA 1992 scheduled inventory was, on the average, 17% below that reported on DOT Form 41 for the ten major passenger air carriers considered. Differences between fuel consumed per mile for general aircraft types (i.e. 737, 747) calculated from 1992 DOT Form 41 data and that calculated from the 1992 NASA scheduled inventory were not a strong function of the size of the aircraft.

For the cargo air carriers considered in the analysis done in Section 2, departures and ground track miles did not match well between the 1992 inventory results and the DOT Form 41 data set. This indicates that the OAG flight schedule used to create NASA scheduled aircraft emissions inventories may not accurately account for some cargo flights. Because the fuel consumed by the cargo portion of the scheduled aircraft fleet is relatively small (6%), the effect of inaccuracies in the cargo schedule on scheduled inventory results is likely to be small. More investigation will be necessary in the future to better understand inaccuracies in the cargo schedule and their overall effect on scheduled emissions inventory calculations.

Section 3 highlighted how closely global fleet operating assumptions match those of one operator's 747-400 fleet. Three major areas were identified that lead to higher aircraft fuel consumption; deterioration effects, increased distance flown and increased weight. The studied aircraft flew an average of 3.8% equivalent further distance (accounting for winds aloft) than the most direct route. This would increase fuel consumption 4.7% on a 5000 mile mission. The inventory model under-predicts actual aircraft cruise gross weight an average of 11.2%. This results in a fuel consumption under-prediction of 9.0% for a 5000 mile mission. Lastly, for the studied carrier's fleet, fuel mileage typically deteriorates about 3.6% due to normal airframe and engine aging. This would add 4.2% more fuel use. In all, for the sample 5000 mile mission, the inventory model will predict a 17.9% increase in fuel consumption when using simplifying operating assumptions that are similar to one carrier's 747-400 fleet characteristics. This agrees well with the results presented in Section 2. The other operating assumptions were not found to have significantly impacted fuel use. Shorter range aircraft will probably exhibit different operating characteristics than those listed since they carry less cargo and will likely be more heavily impacted by air traffic control constraints. Additionally no significant seasonal variations were found with this operator's 747-400 fleet.

Section 4 showed that for each of the four aircraft/engine combinations studied, total NOx and CO_2 created on a single mission varied linearly with payload. Analysis of 747-400 data showed that factors for scaling CO_2 and NOx for different loadings created using single mission data for a given aircraft may be useful in scaling global totals of these emittants. When applying these scale factors on a cell by cell basis to three dimensional global emissions inventory results, incorrect spatial distributions of global emissions are expected to result because of flight altitude changes and changes in fuel burn rate.

This report has provided an insight into the accounting of fuel use between actual and modeled commercial jet aircraft fleets. In addition, individual factors that affect airplane fuel consumption and NOx emissions were studied. These individual factors likely account for much of the difference between the fuel consumption calculated for the NASA 1992 scheduled inventory aircraft fleet and that actually reported by airlines. Further study of in-service aircraft to account for more aircraft types and different typical missions would likely contribute to better understanding of the effects of actual operations including air traffic control, variations in payload, cargo, and meteorology.

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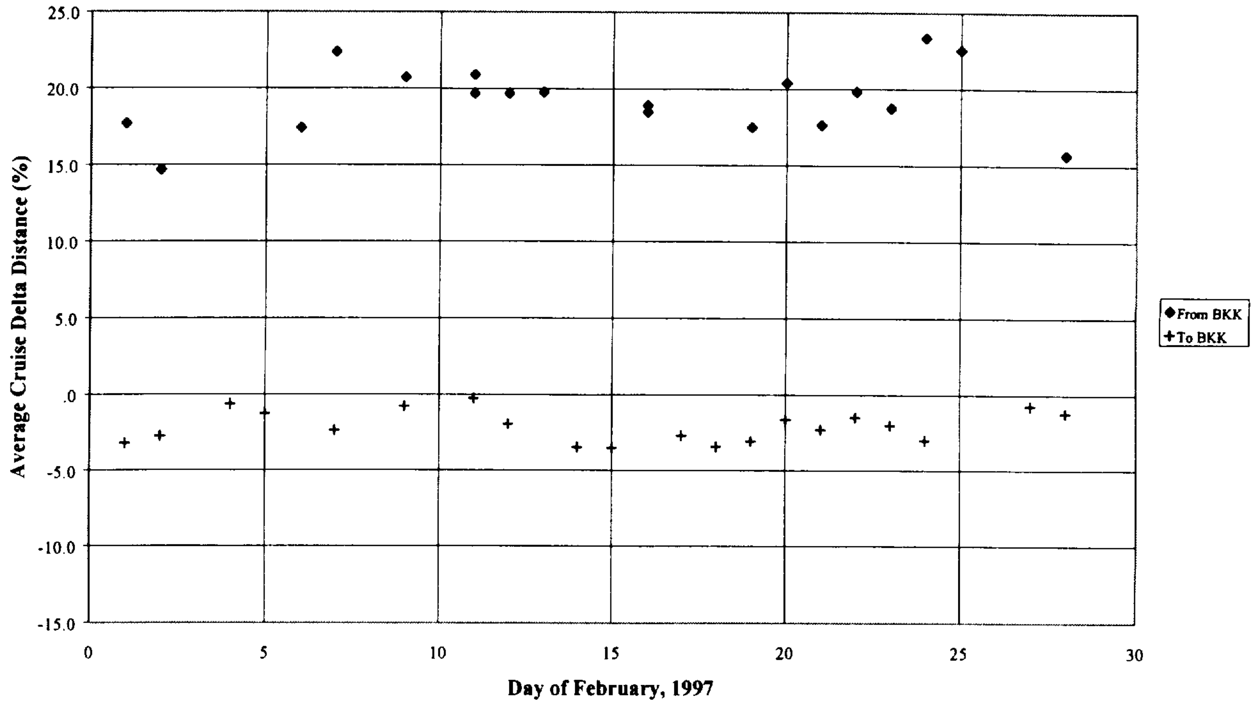
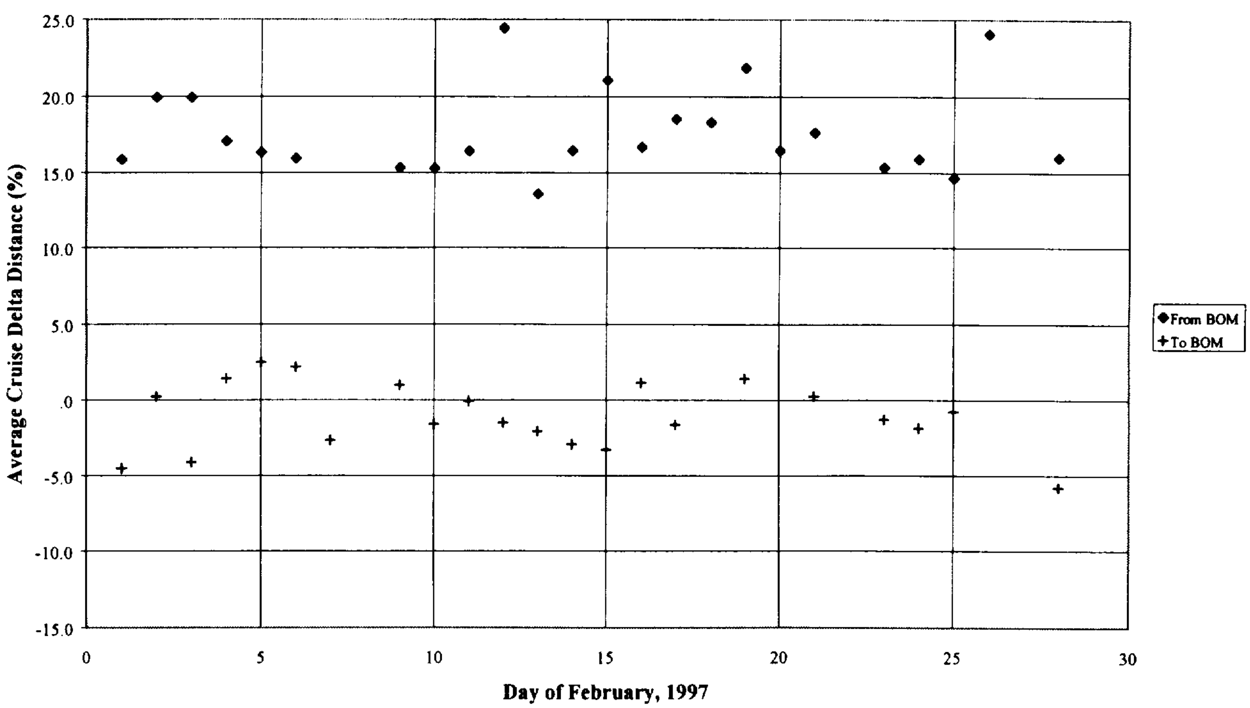
APPENDIX A
Great Circle Vs. Actual Distance Comparison

The following figures provide distance detail for each flight the operator ran during February 1997. For any particular flight, the difference between a no-winds great circle route and the "still air distance" route is illustrated. Thus, two variables are accounted for in this difference in distance number -- winds aloft and ground track. These differences represent what an inventory model would predict and what actually was flown.

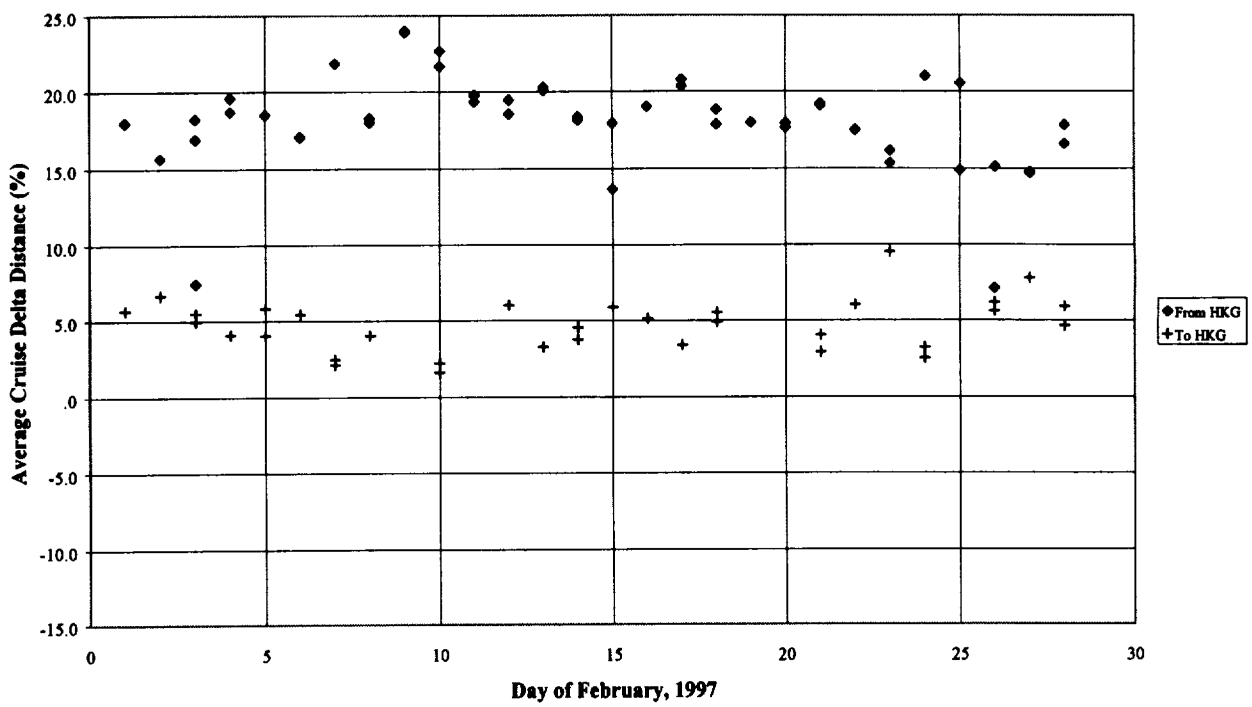
747-400 Cruise 'Still Air Distance' Vs. 'Great Circle' Route for LHR/BKK



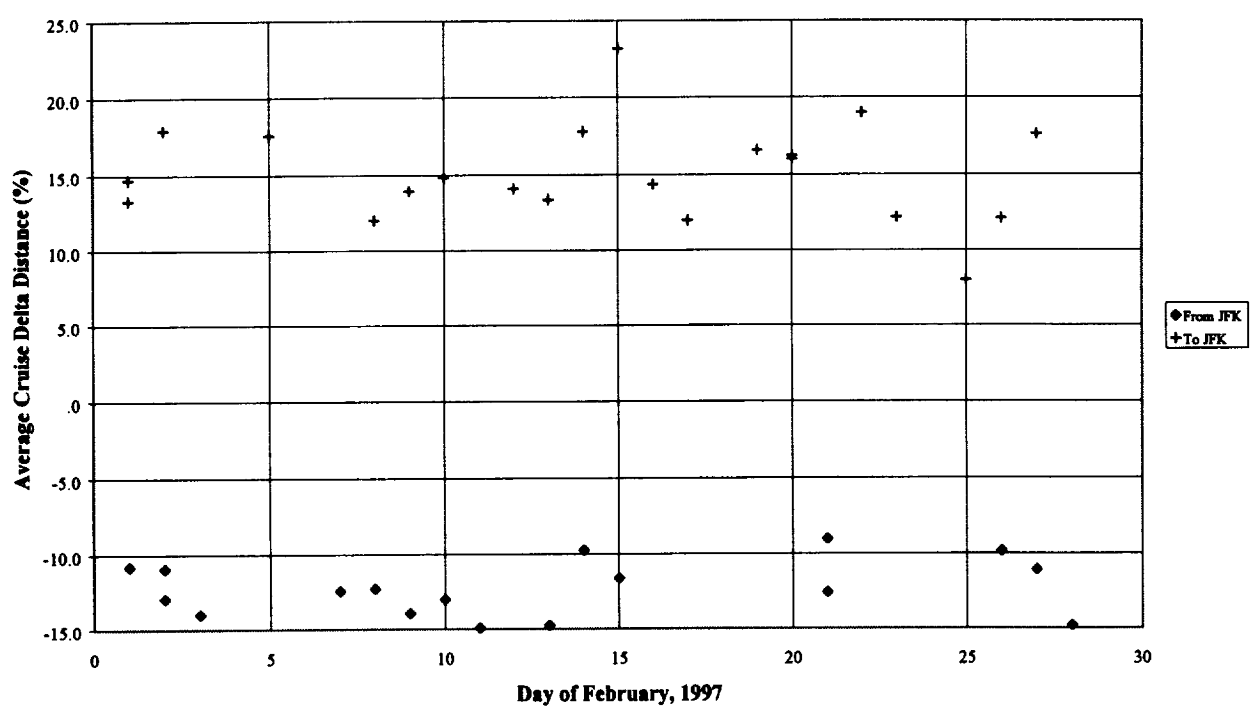
747-400 Cruise 'Still Air Distance' Vs. 'Great Circle' Route for LHR/BOM

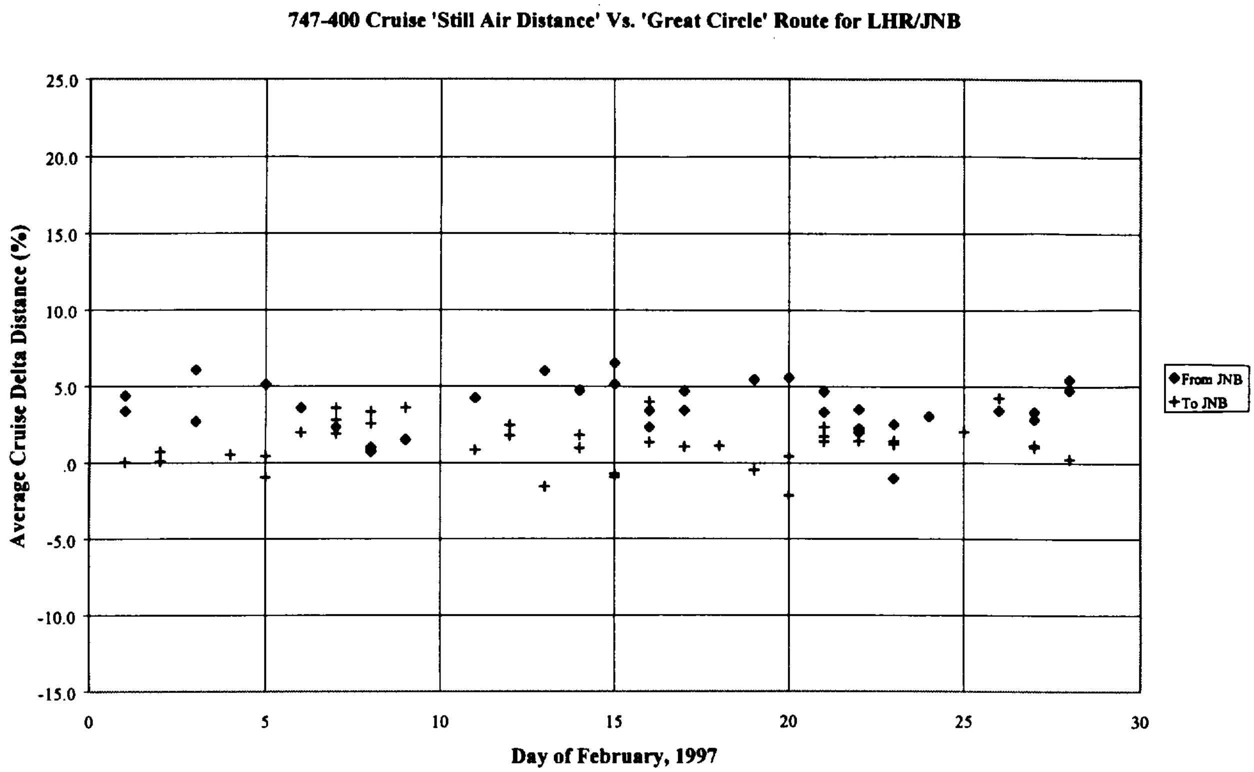


747-400 Cruise 'Still Air Distance' Vs. 'Great Circle' Route for LHR/HKG

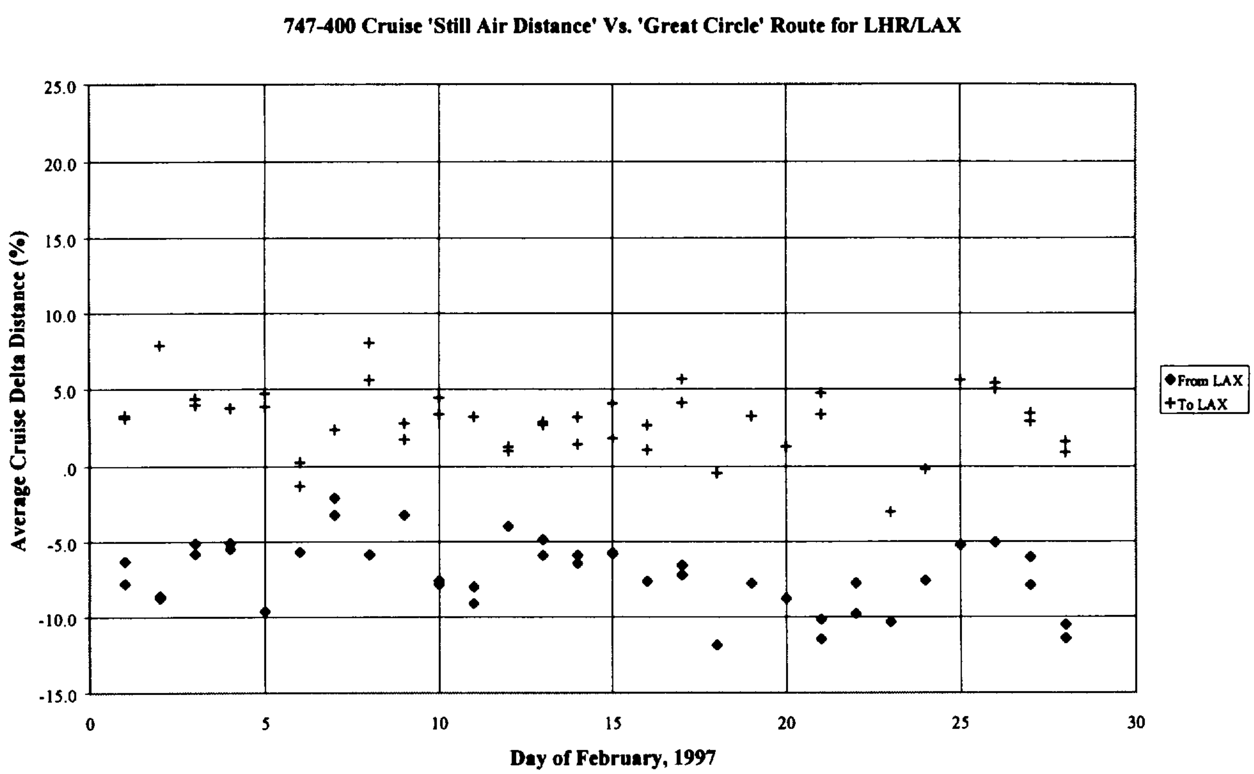


747-400 Cruise 'Still Air Distance' Vs. 'Great Circle' Route for LHR/JFK



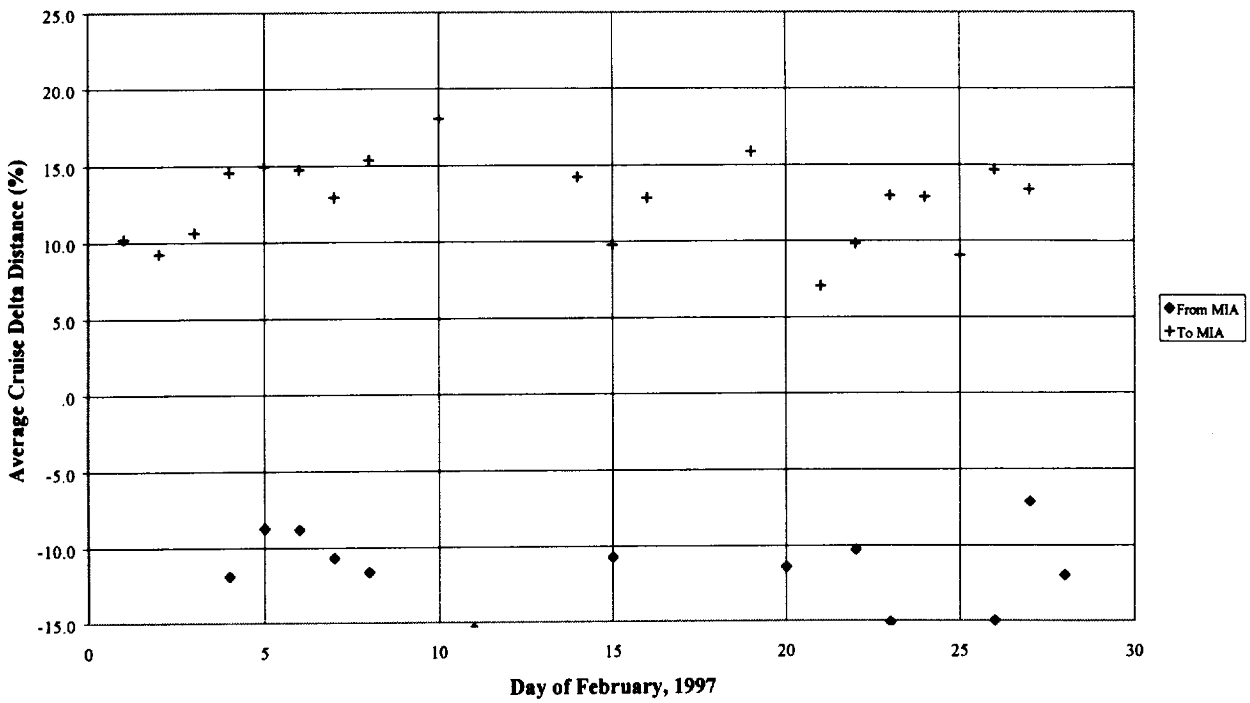


747-400 Cruise 'Still Air Distance' Vs. 'Great Circle' Route for LHR/JNB
Average Cruise Delta Distance (%)
25.0
20.0
15.0
10.0
5.0
.0
-5.0
-10.0
-15.0
0
5
10
15
20
25
30
Day of February, 1997
From JNB
To JNB

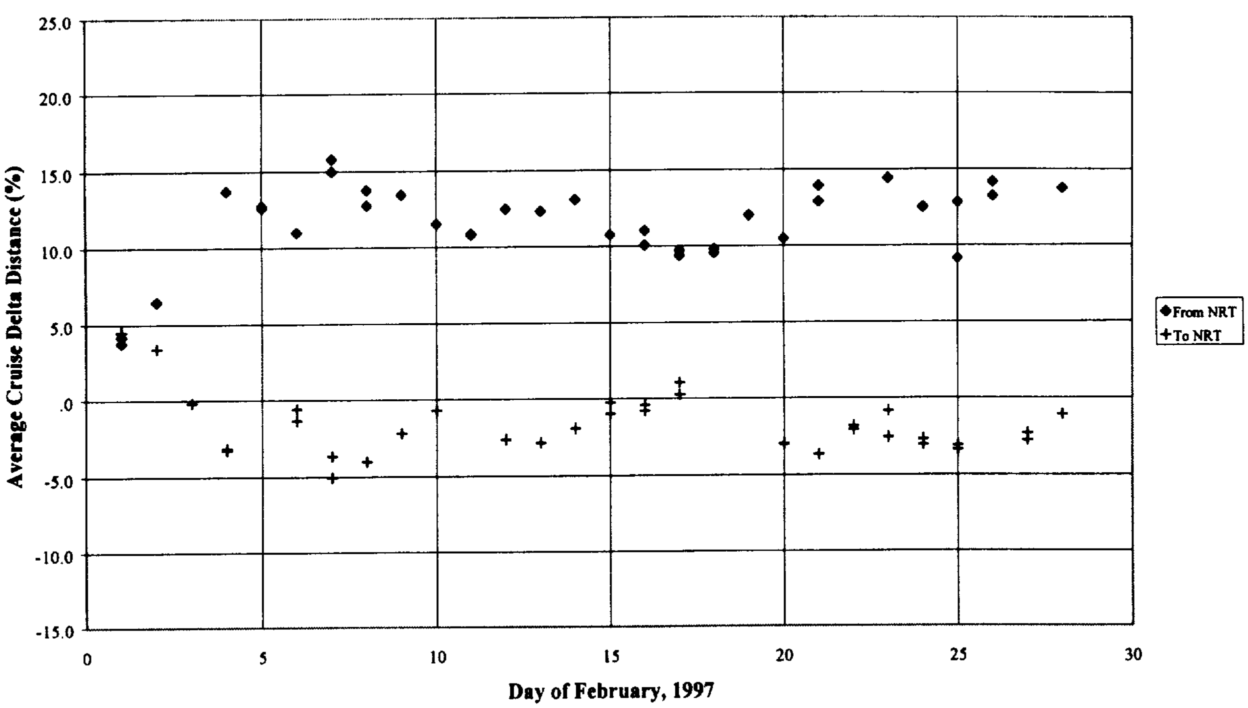


747-400 Cruise 'Still Air Distance' Vs. 'Great Circle' Route for LHR/LAX
Average Cruise Delta Distance (%)
25.0
20.0
15.0
10.0
5.0
.0
-5.0
-10.0
-15.0
0
5
10
15
20
25
30
Day of February, 1997
From LAX
To LAX

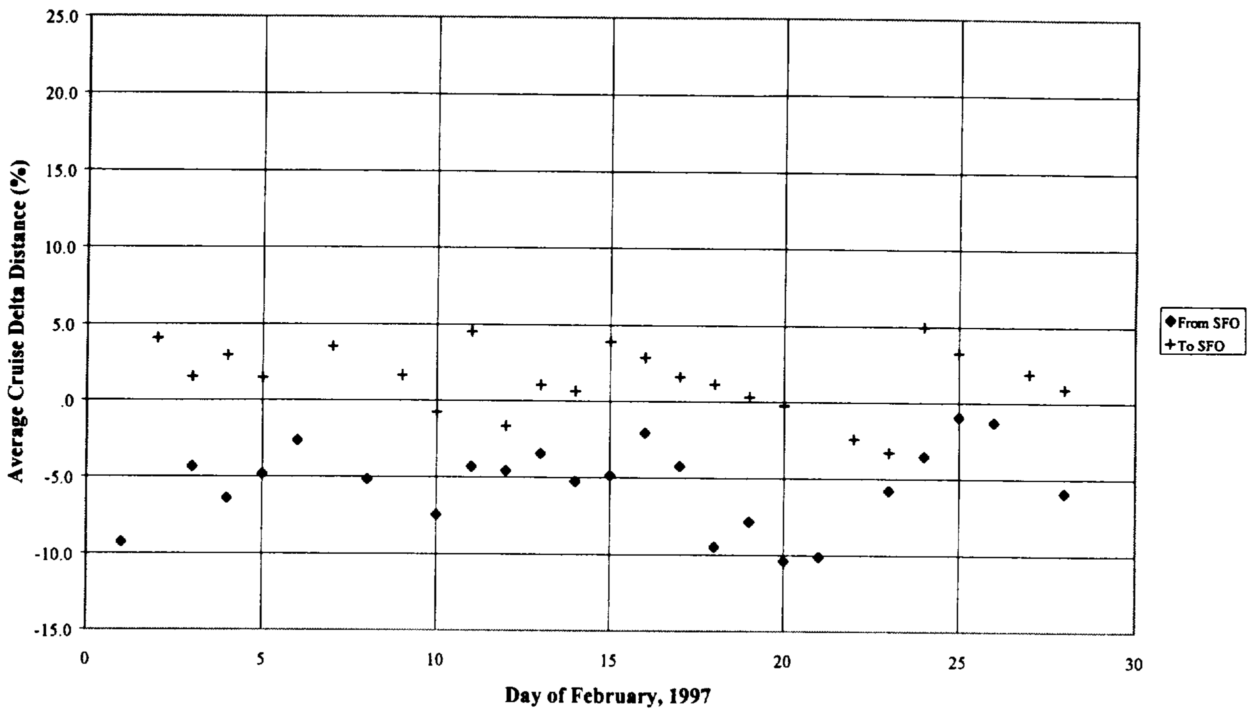
747-400 Cruise 'Still Air Distance' Vs. 'Great Circle' Route for LHR/MIA



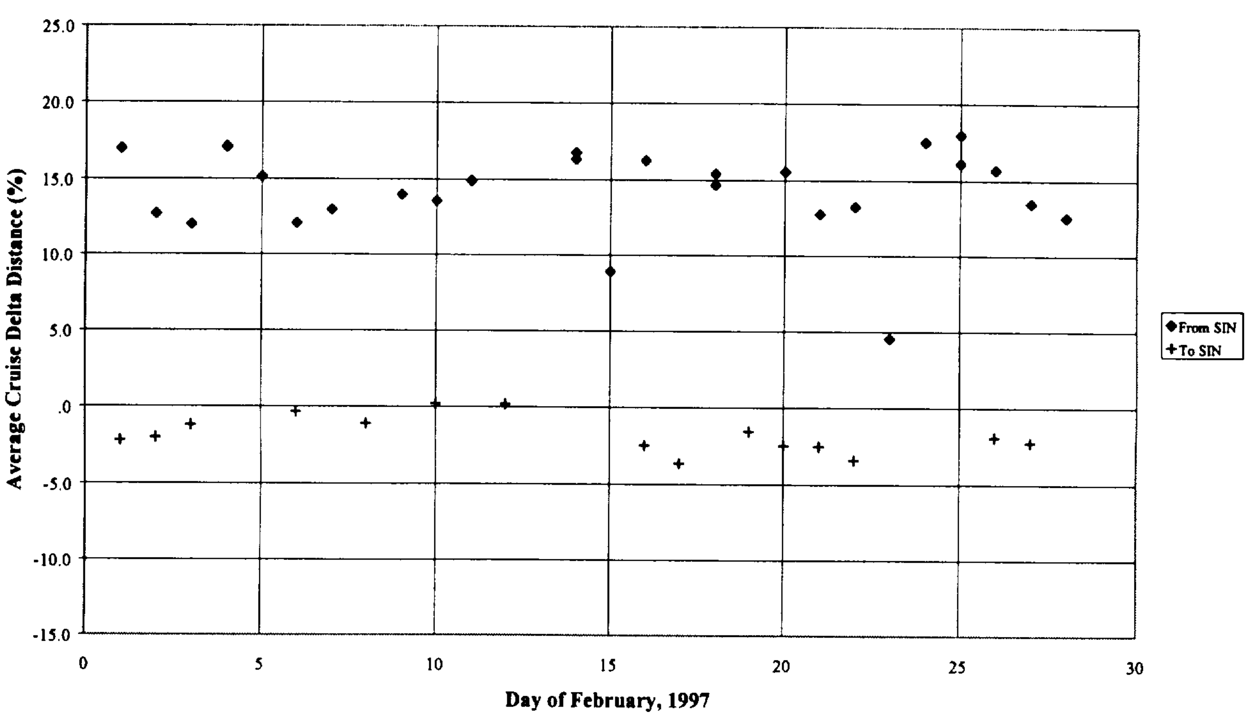
747-400 Cruise 'Still Air Distance' Vs. 'Great Circle' Route for LHR/NRT



747-400 Cruise 'Still Air Distance' Vs. 'Great Circle' Route for LHR/SFO



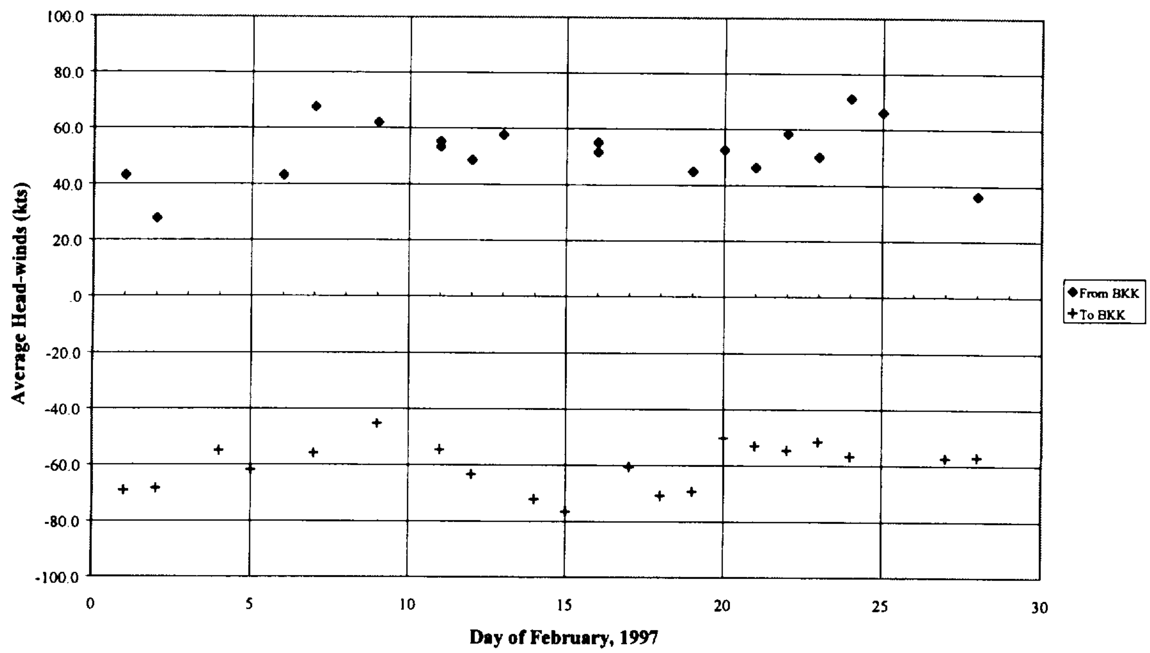
747-400 Cruise 'Still Air Distance' Vs. 'Great Circle' Route for LHR/SIN



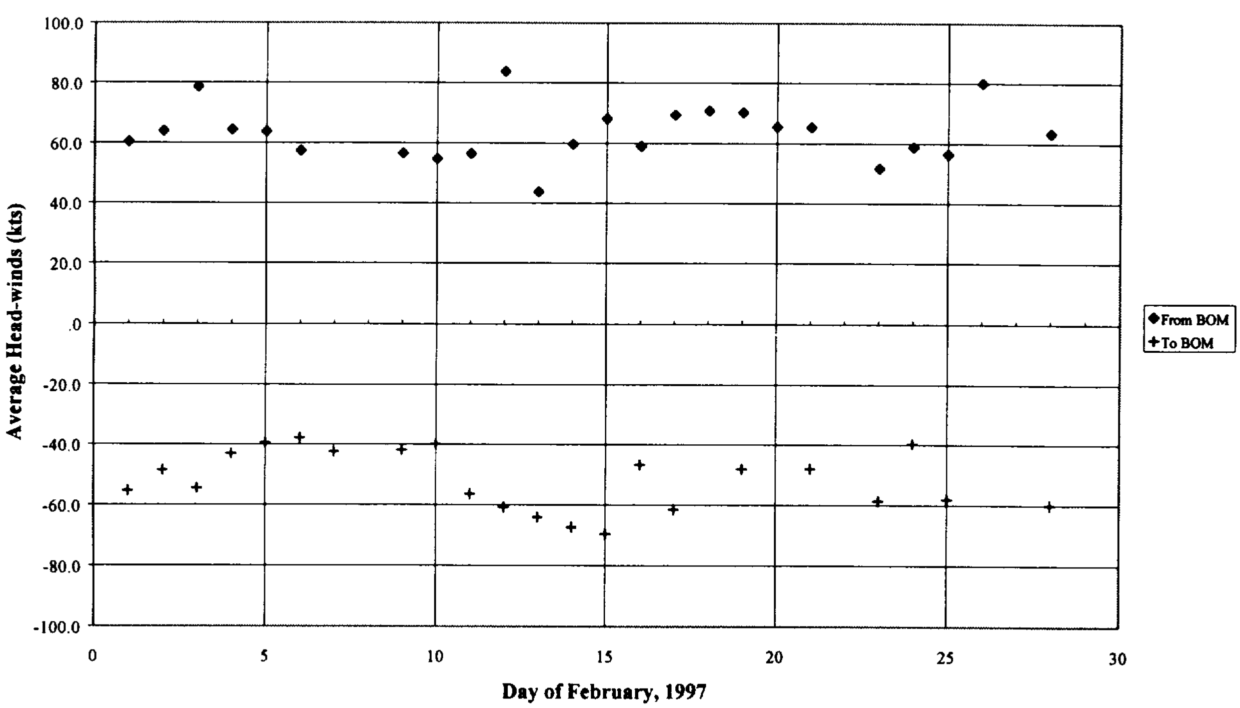
APPENDIX B
Average Head Winds

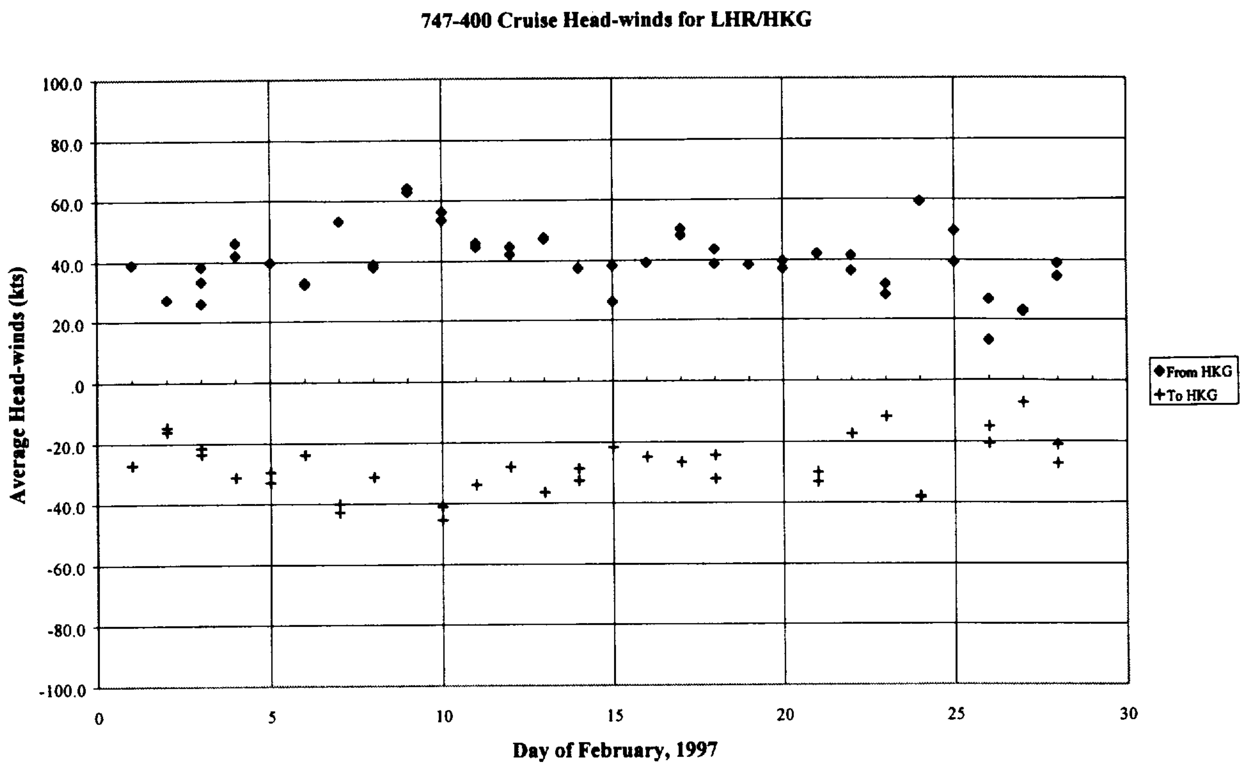
The following figures give more detail on the winds aloft that each flight experienced during February 1997 for the operator's fleet. The winds aloft value (Y axis) is an average of all the winds encountered during the cruise portion of the flight, positive values indicating a head-wind while negative values indicate a tail wind.

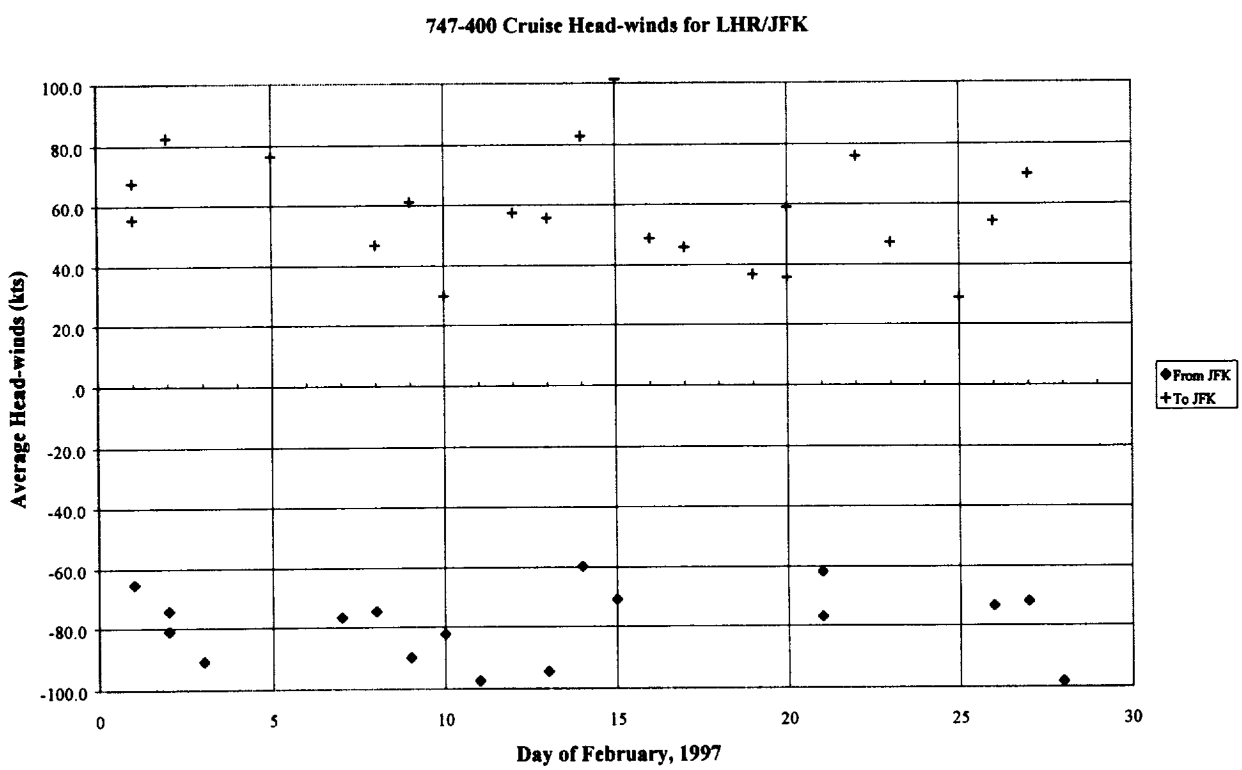
747-400 Cruise Head-winds for LHR/BKK

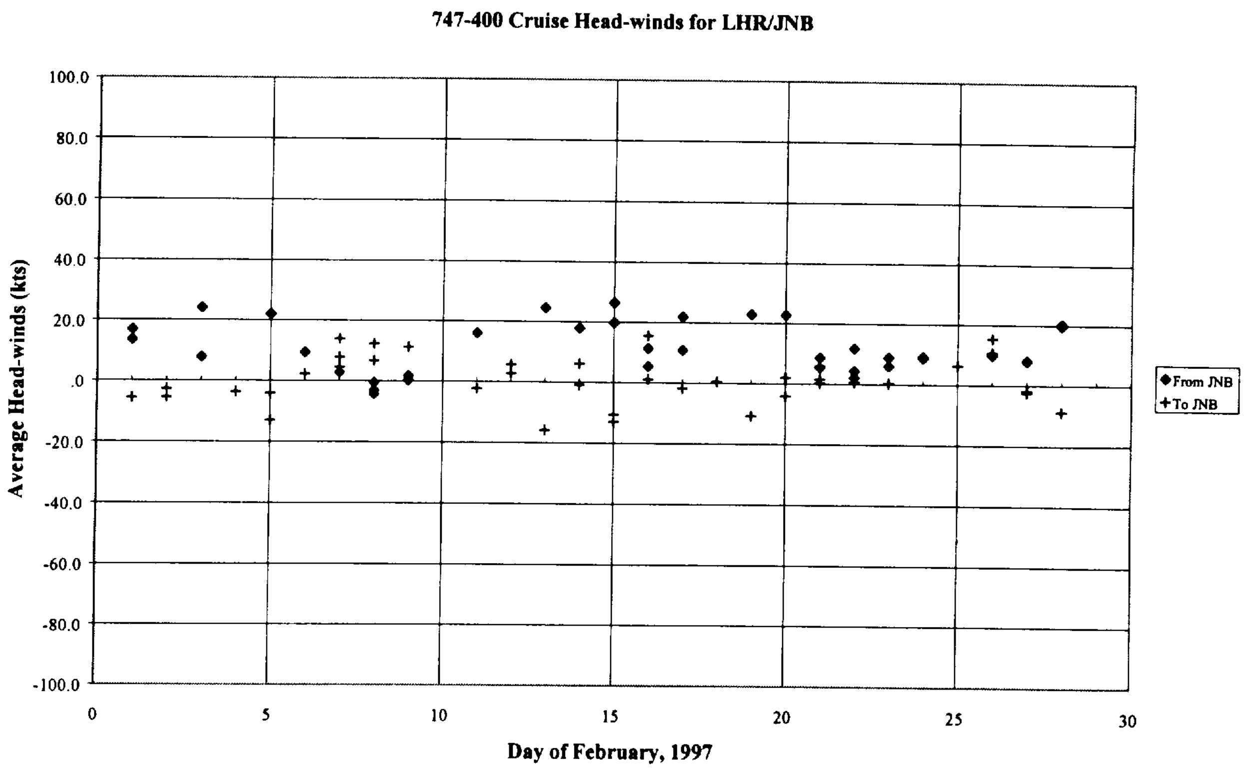


747-400 Cruise Head-winds for LHR/BOM




747-400 Cruise Head-winds for LHR/HKG
Average Head-winds (kts)
100.0
80.0
60.0
40.0
20.0
.0
-20.0
-40.0
-60.0
-80.0
-100.0
0
5
10
15
20
25
30
Day of February, 1997
From HKG
To HKG


747-400 Cruise Head-winds for LHR/JFK
Average Head-winds (kts)
100.0
80.0
60.0
40.0
20.0
.0
-20.0
-40.0
-60.0
-80.0
-100.0
0
5
10
15
20
25
30
Day of February, 1997
From JFK
To JFK


747-400 Cruise Head-winds for LHR/JNB
Average Head-winds (kts)
100.0
80.0
60.0
40.0
20.0
.0
-20.0
-40.0
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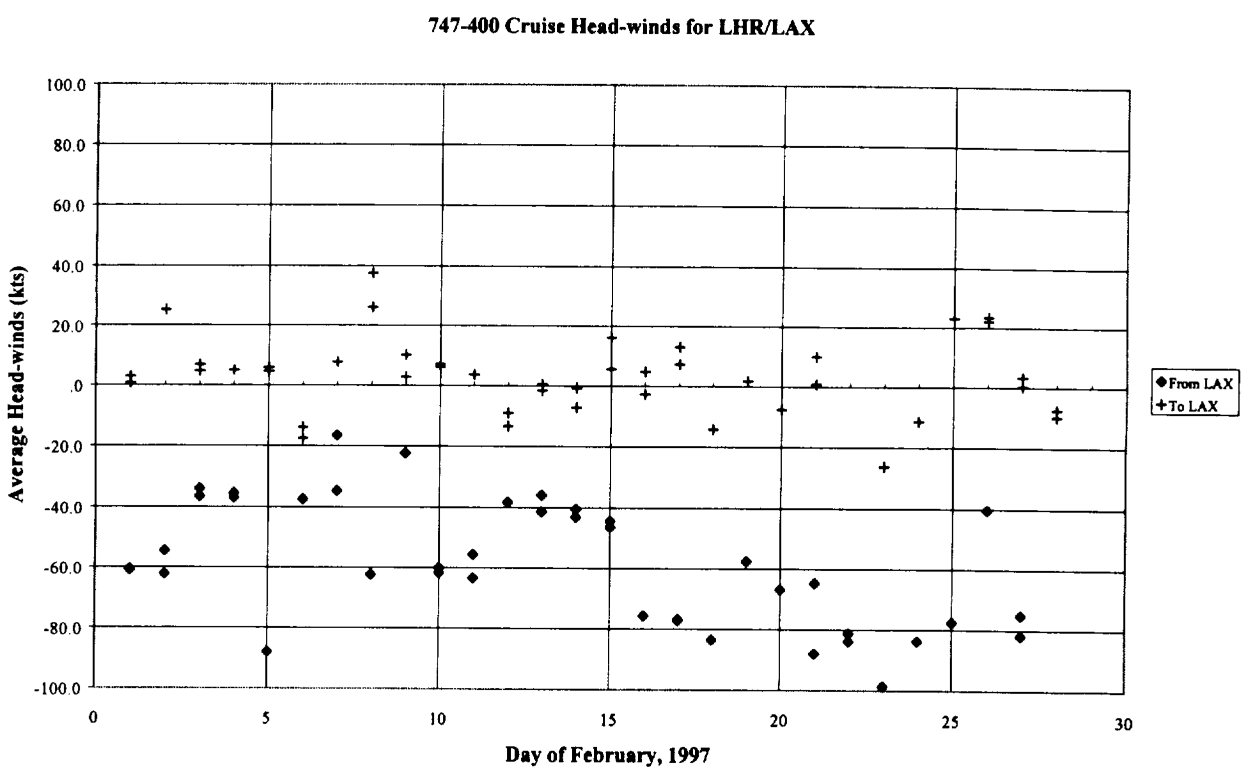
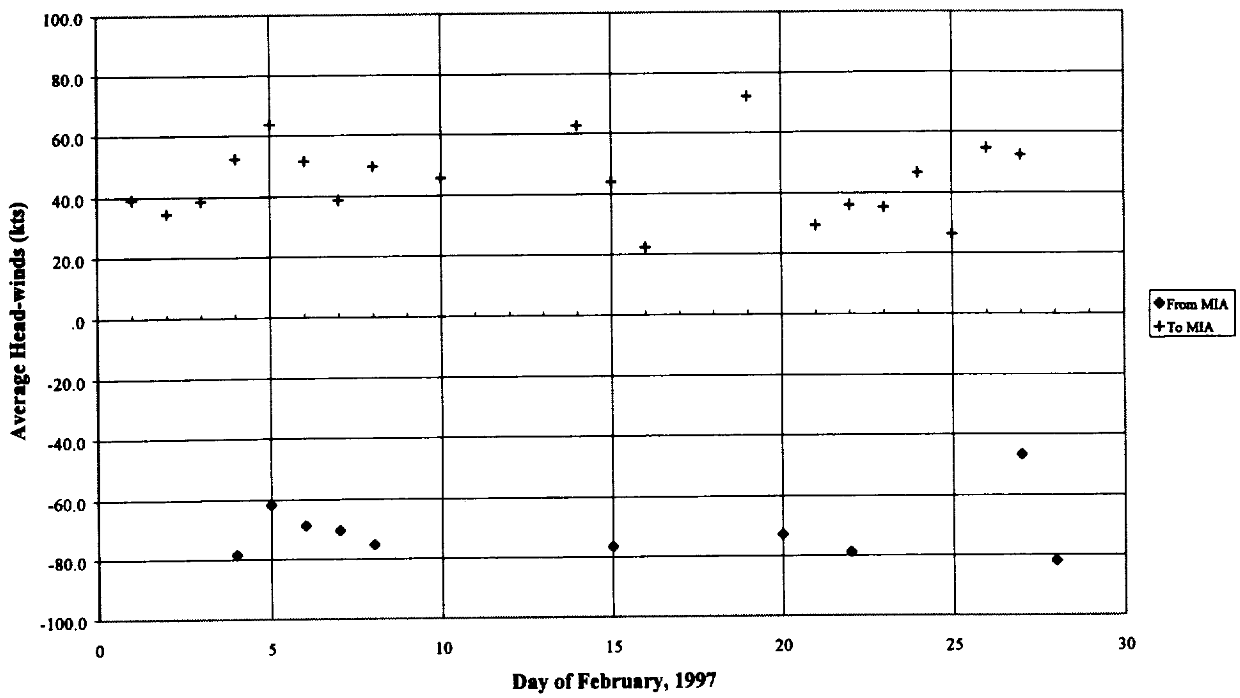
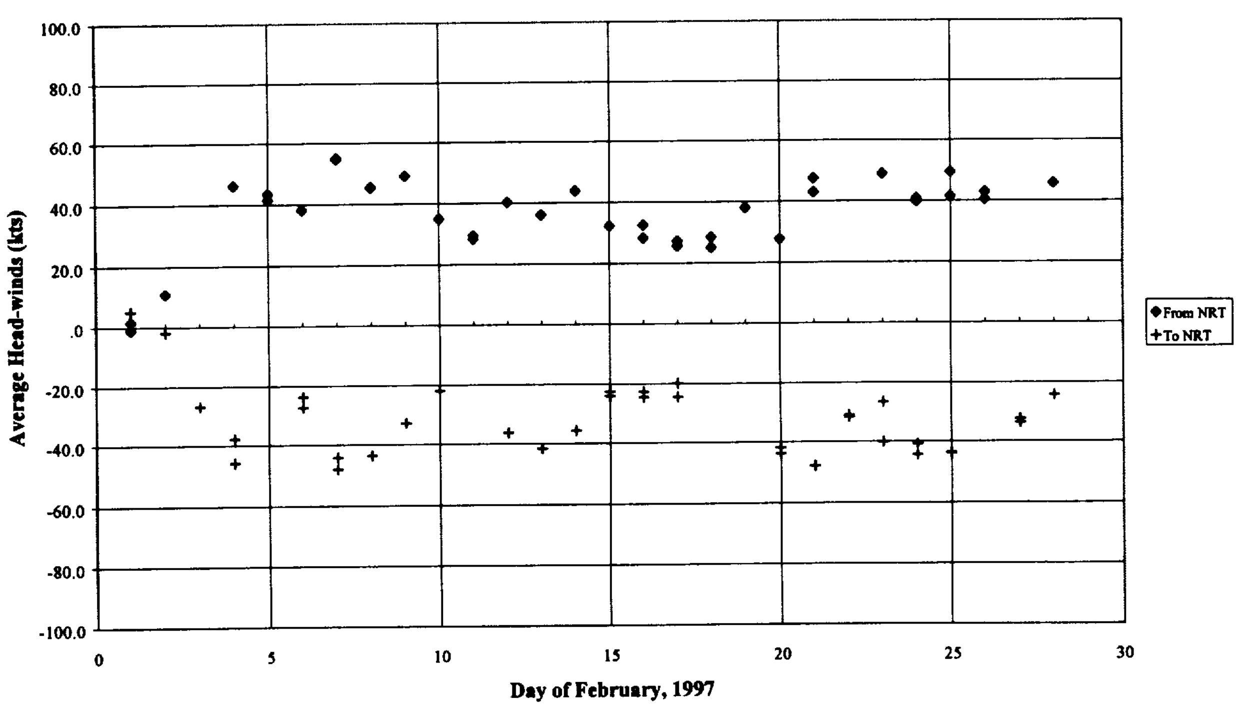
0
5
10
15
20
25
30
Day of February, 1997
From JNB
To JNB

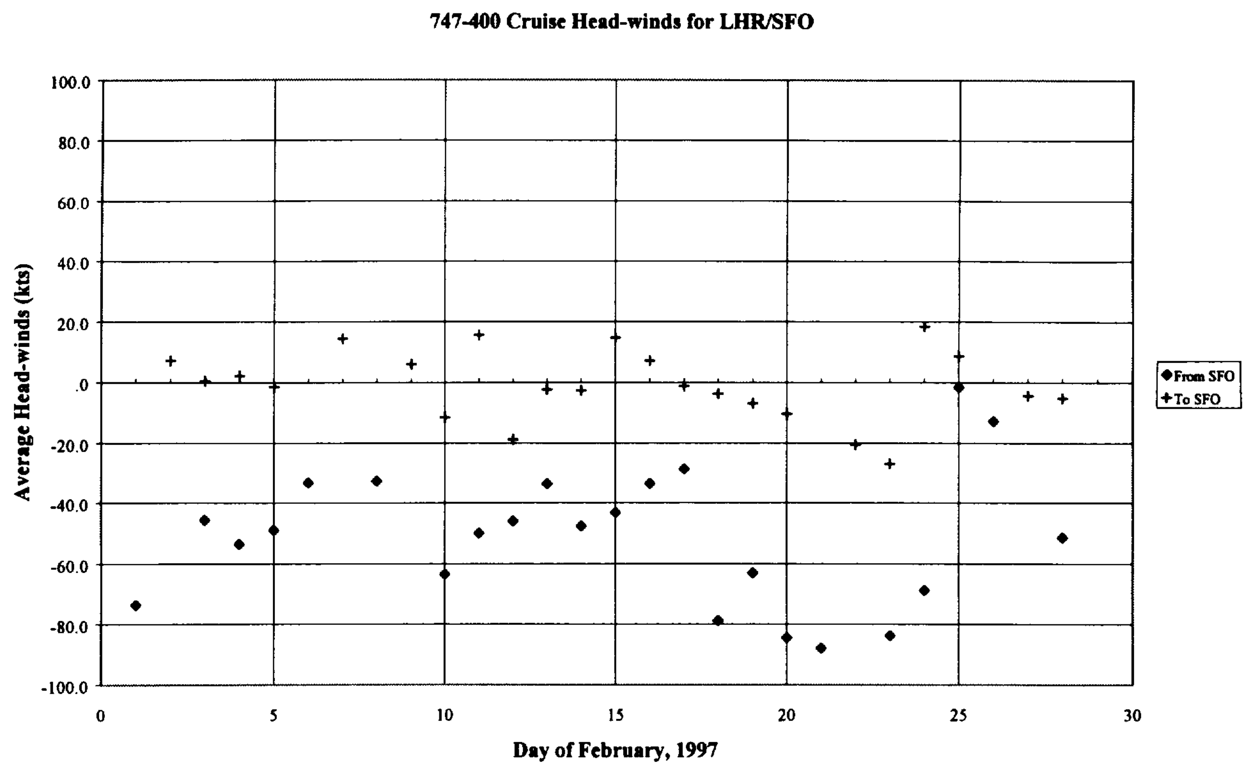

747-400 Cruise Head-winds for LHR/LAX
Average Head-winds (kts)
100.0
80.0
60.0
40.0
20.0
.0
-20.0
-40.0
-60.0
-80.0
-100.0
0
5
10
15
20
25
30
Day of February, 1997
From LAX
To LAX

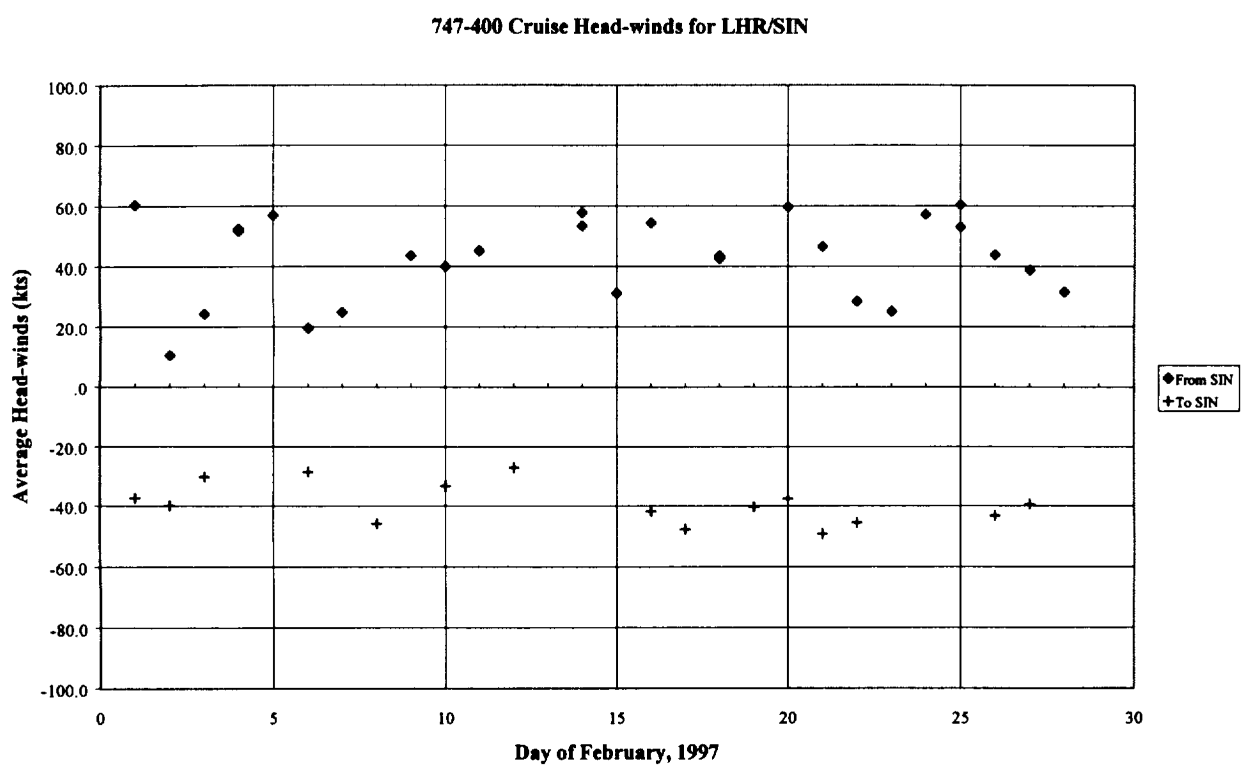
747-400 Cruise Head-winds for LHR/MIA



747-400 Cruise Head-winds for LHR/NRT

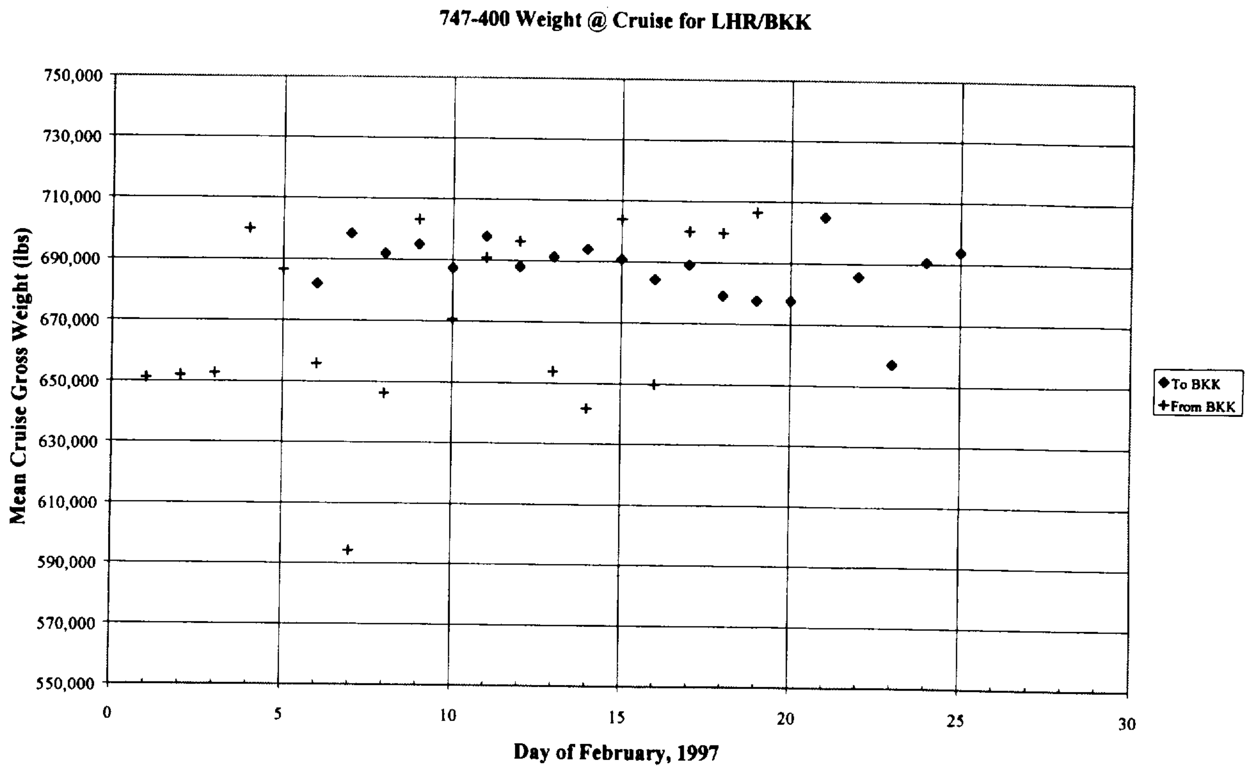


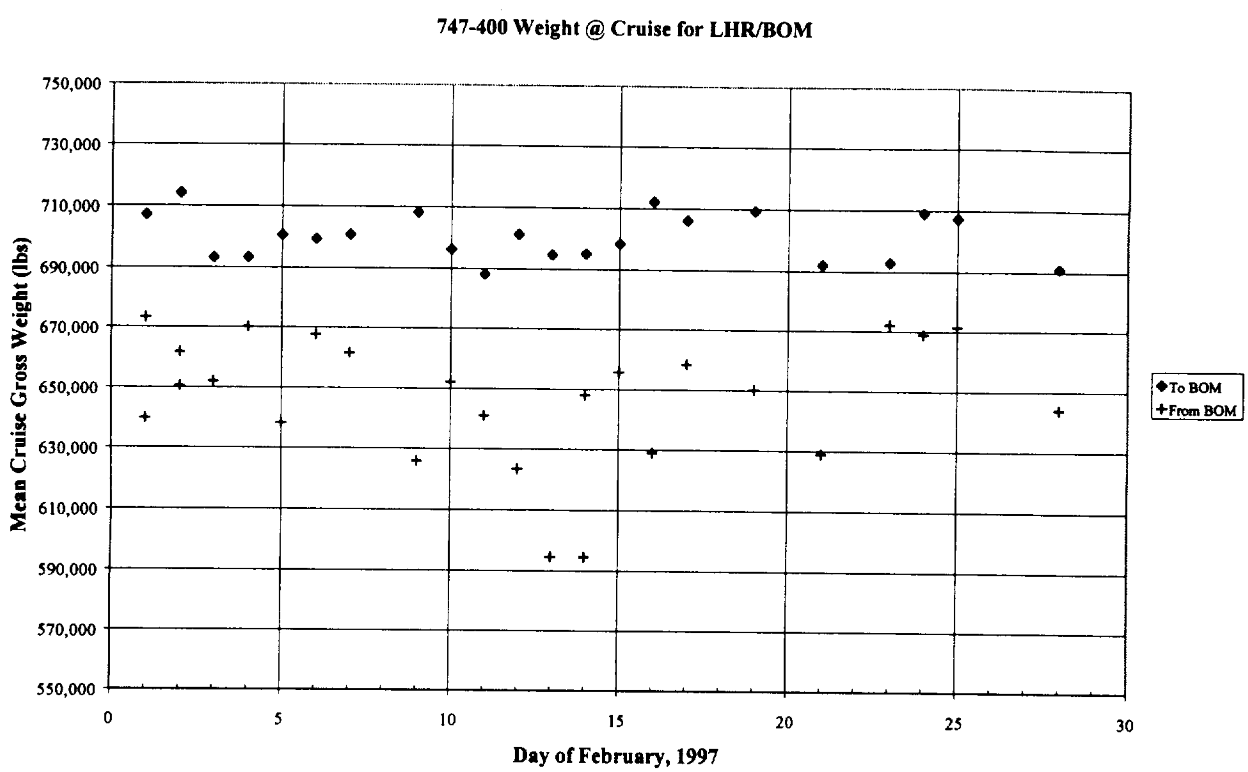

747-400 Cruise Head-winds for LHR/SFO
Average Head-winds (kts)
Day of February, 1997
From SFO
To SFO

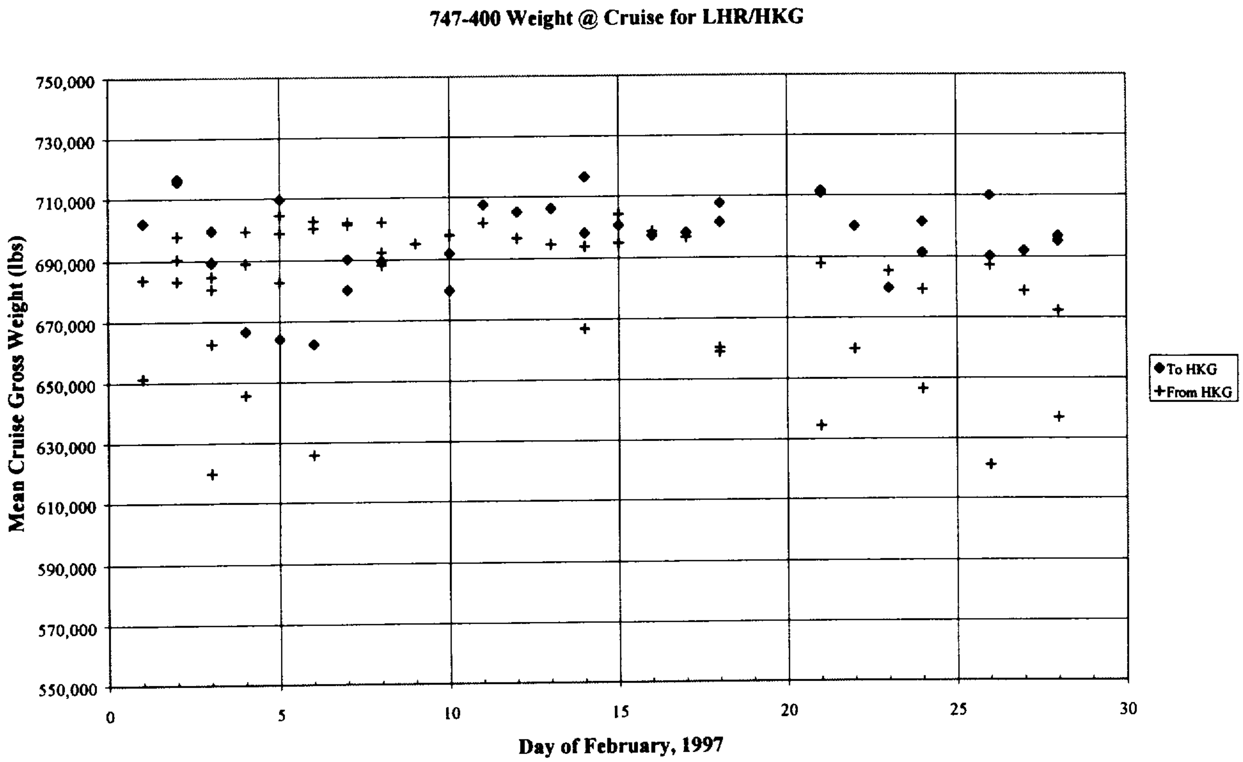

747-400 Cruise Head-winds for LHR/SIN
Average Head-winds (kts)
Day of February, 1997
From SIN
To SIN

APPENDIX C - Mean Cruise Weight Data

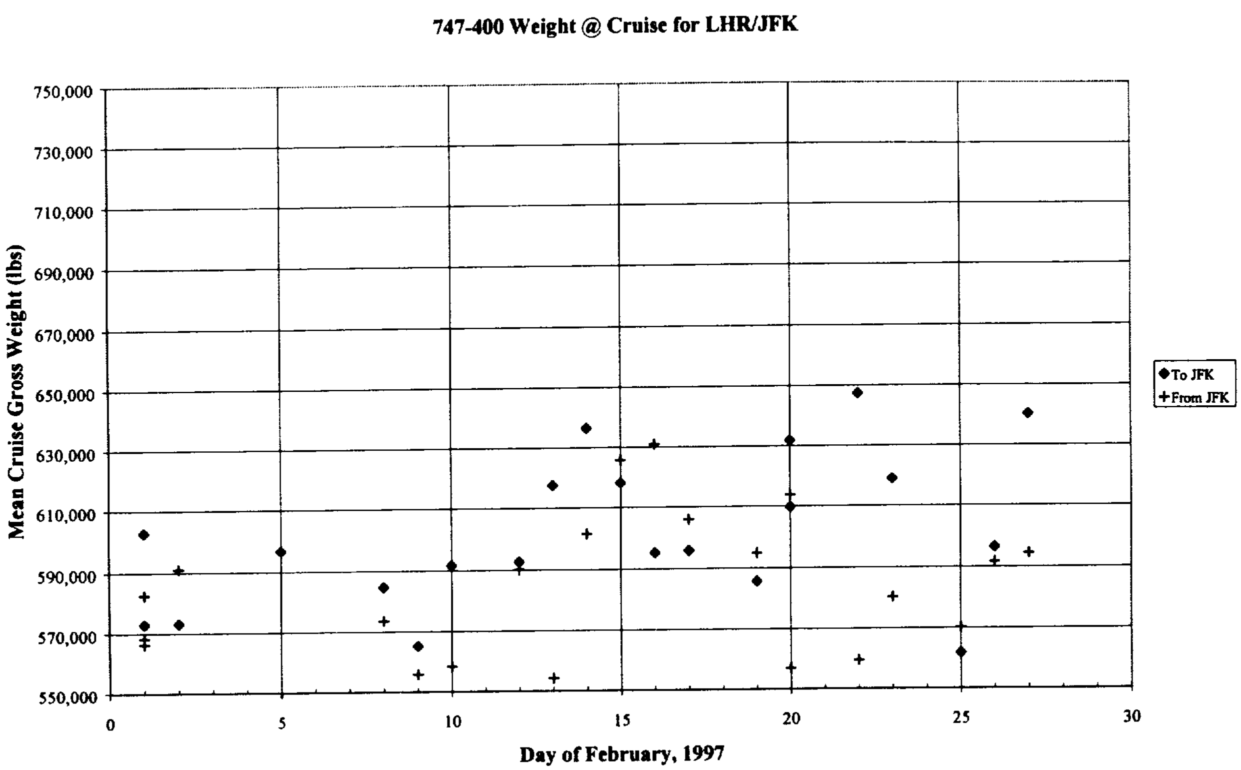
The following figures detail the computed average cruise gross weight for each of the operator's 747-400 flights flown during February 1997. The figures are grouped by city-pair.


747-400 Weight @ Cruise for LHR/BKK
Mean Cruise Gross Weight (lbs)
750,000
730,000
710,000
690,000
670,000
650,000
630,000
610,000
590,000
570,000
550,000
0
5
10
15
20
25
30
Day of February, 1997
To BKK
From BKK


747-400 Weight @ Cruise for LHR/BOM
Mean Cruise Gross Weight (lbs)
750,000
730,000
710,000
690,000
670,000
650,000
630,000
610,000
590,000
570,000
550,000
0
5
10
15
20
25
30
Day of February, 1997
To BOM
From BOM

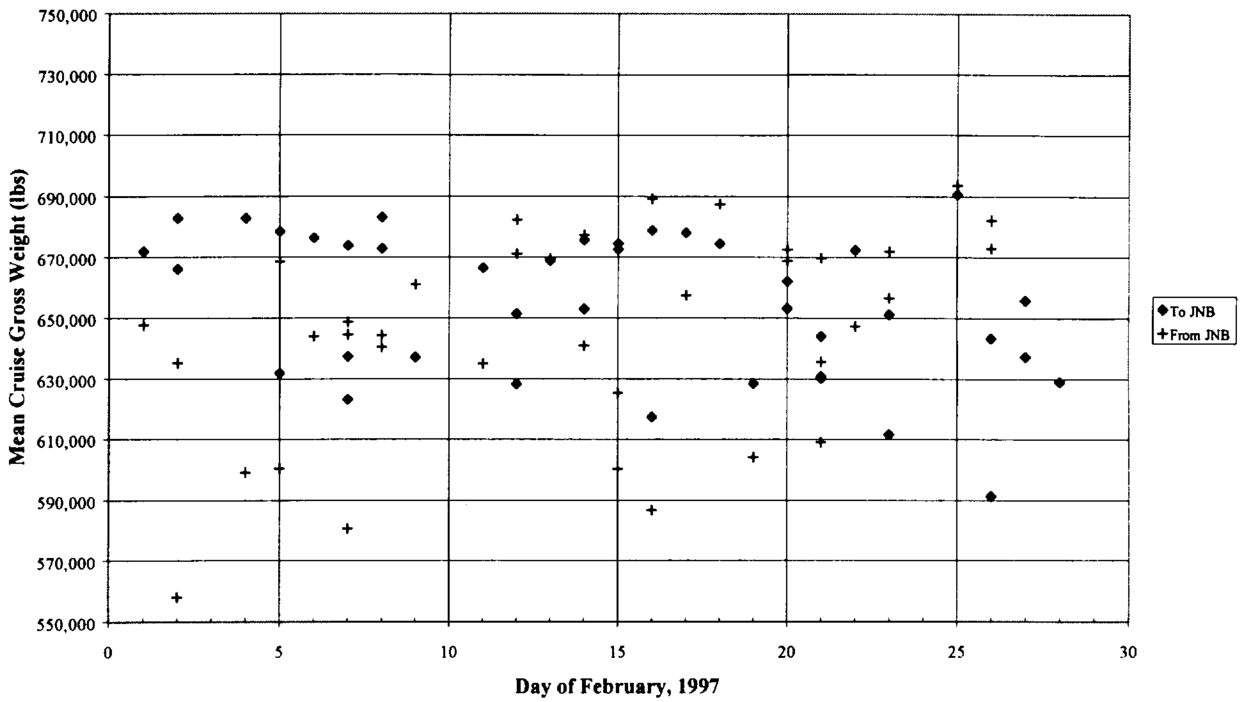


747-400 Weight @ Cruise for LHR/HKG
750,000
730,000
710,000
690,000
670,000
650,000
630,000
610,000
590,000
570,000
550,000
Mean Cruise Gross Weight (lbs)
0
5
10
15
20
25
30
Day of February, 1997
To HKG
From HKG

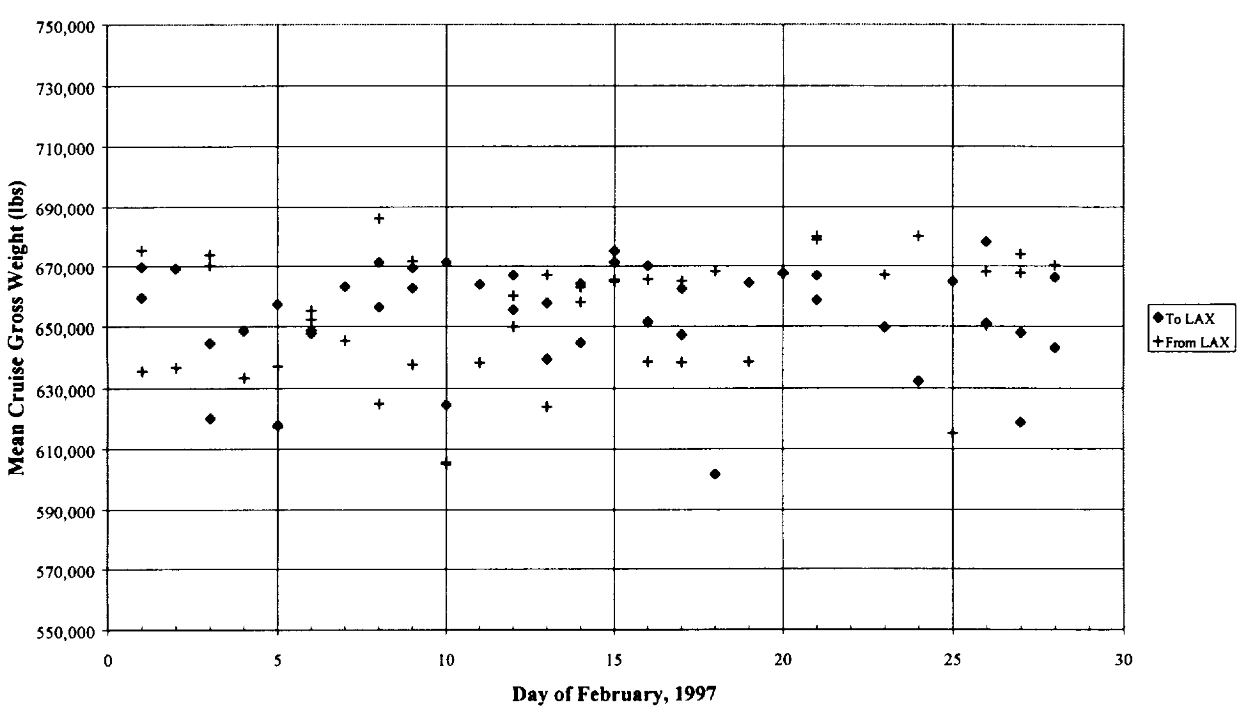


747-400 Weight @ Cruise for LHR/JFK
750,000
730,000
710,000
690,000
670,000
650,000
630,000
610,000
590,000
570,000
550,000
Mean Cruise Gross Weight (lbs)
0
5
10
15
20
25
30
Day of February, 1997
To JFK
From JFK

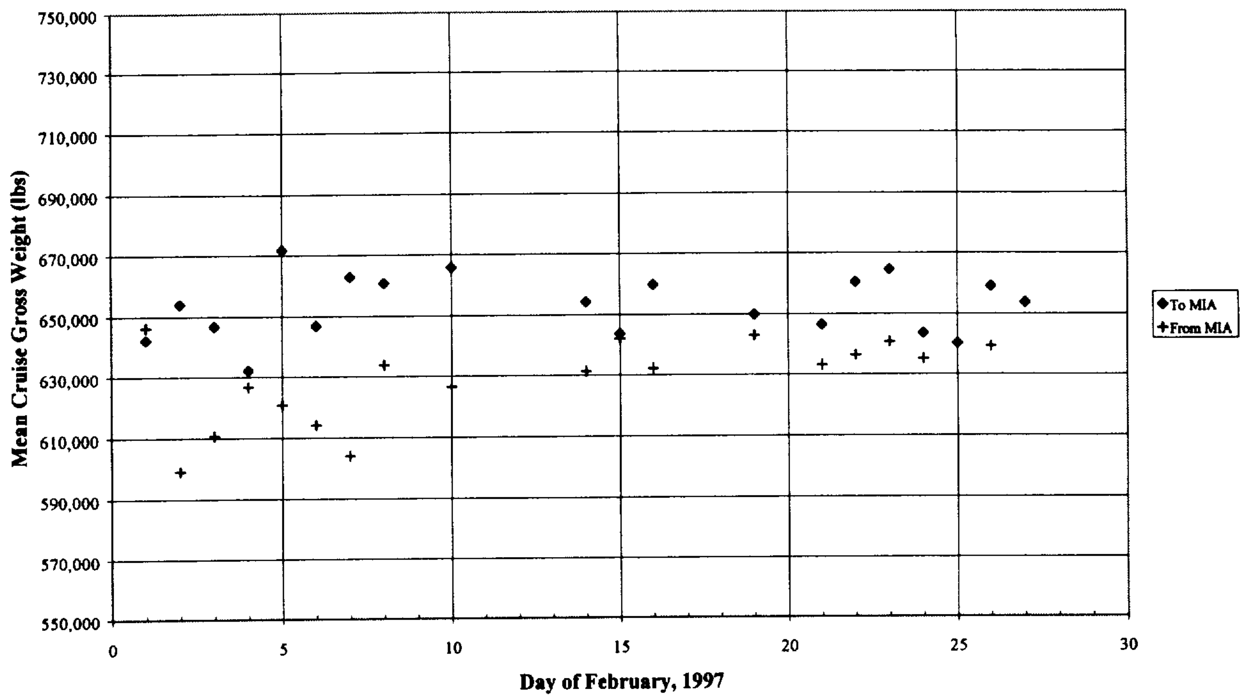
747-400 Weight @ Cruise for LHR/JNB



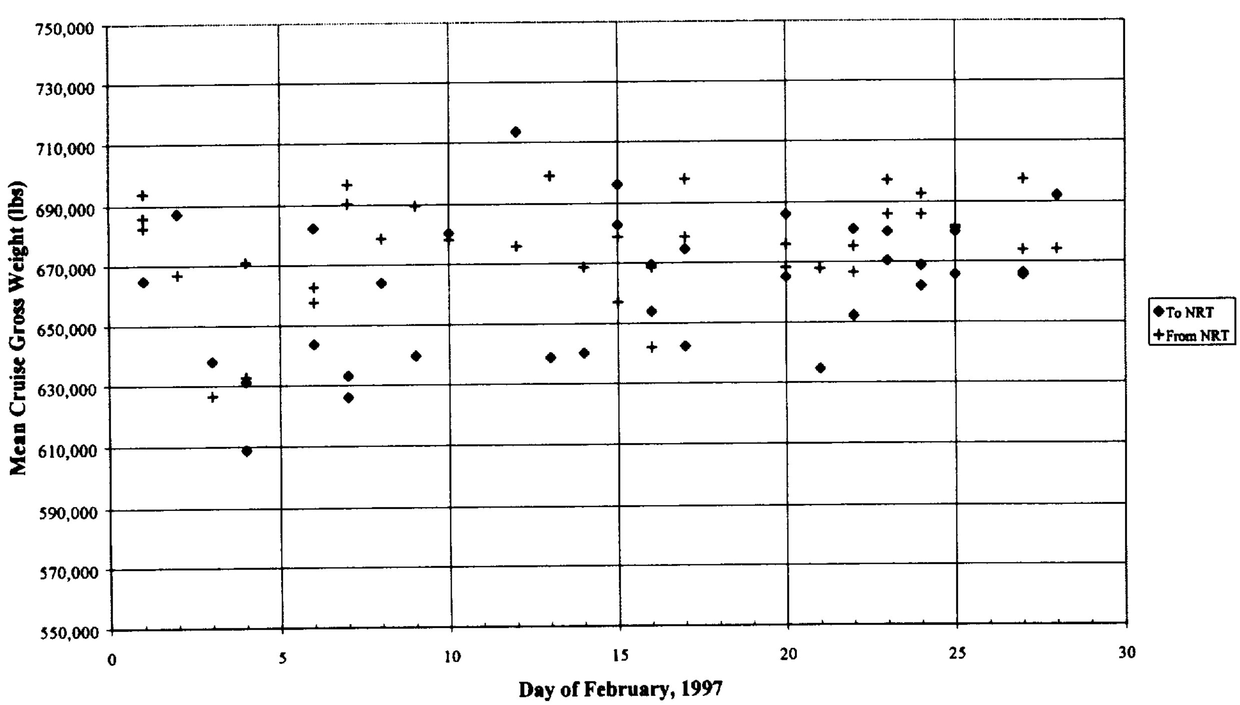
747-400 Weight @ Cruise for LHR/LAX



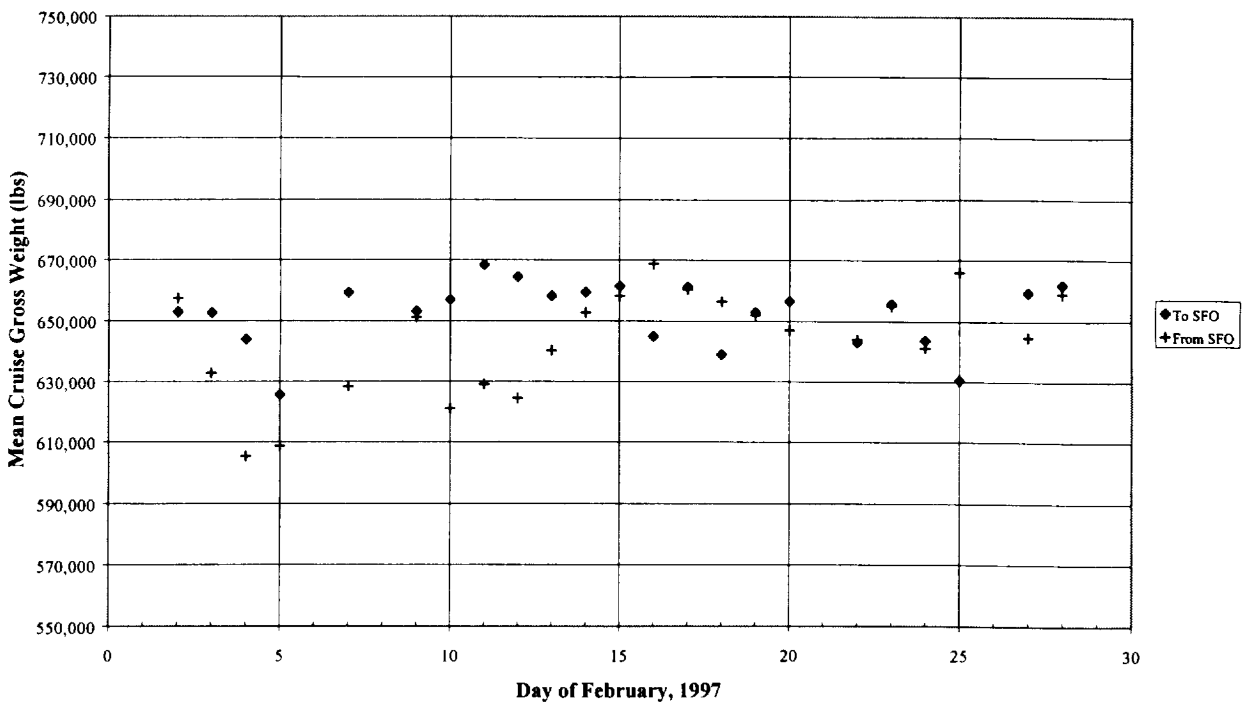
747-400 Weight @ Cruise for LHR/MIA



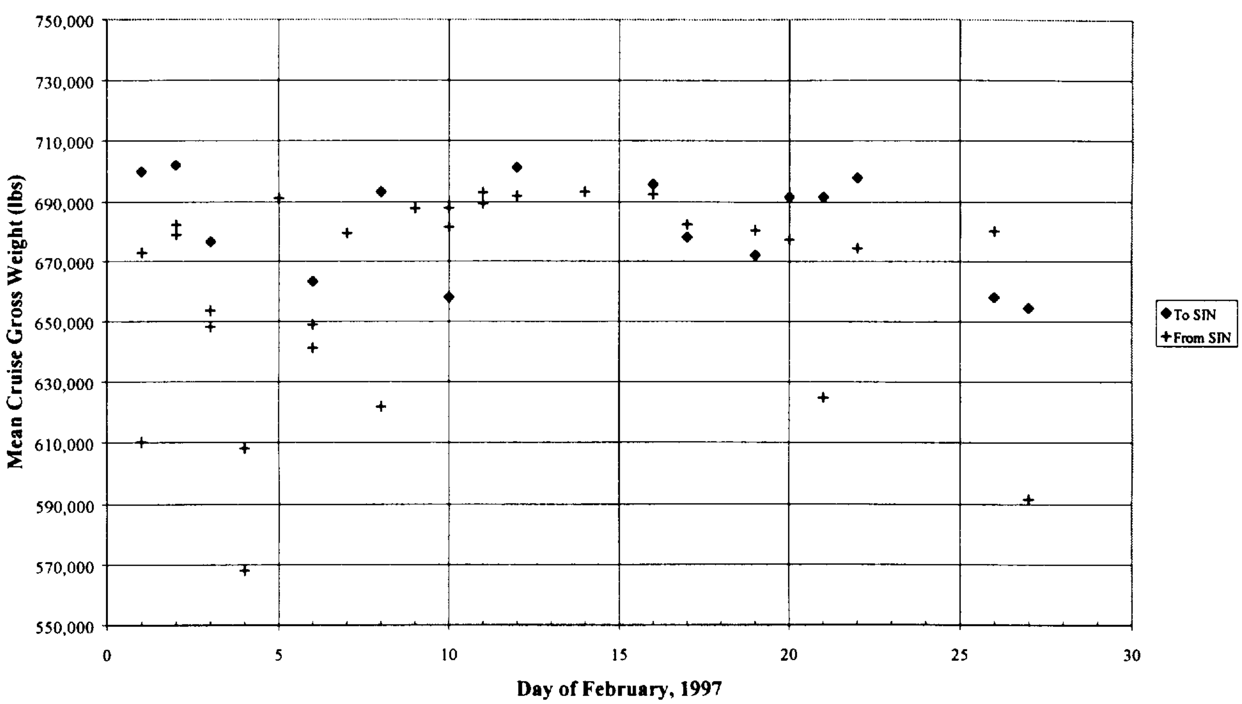
747-400 Weight @ Cruise for LHR/NRT



747-400 Weight @ Cruise for LHR/SFO



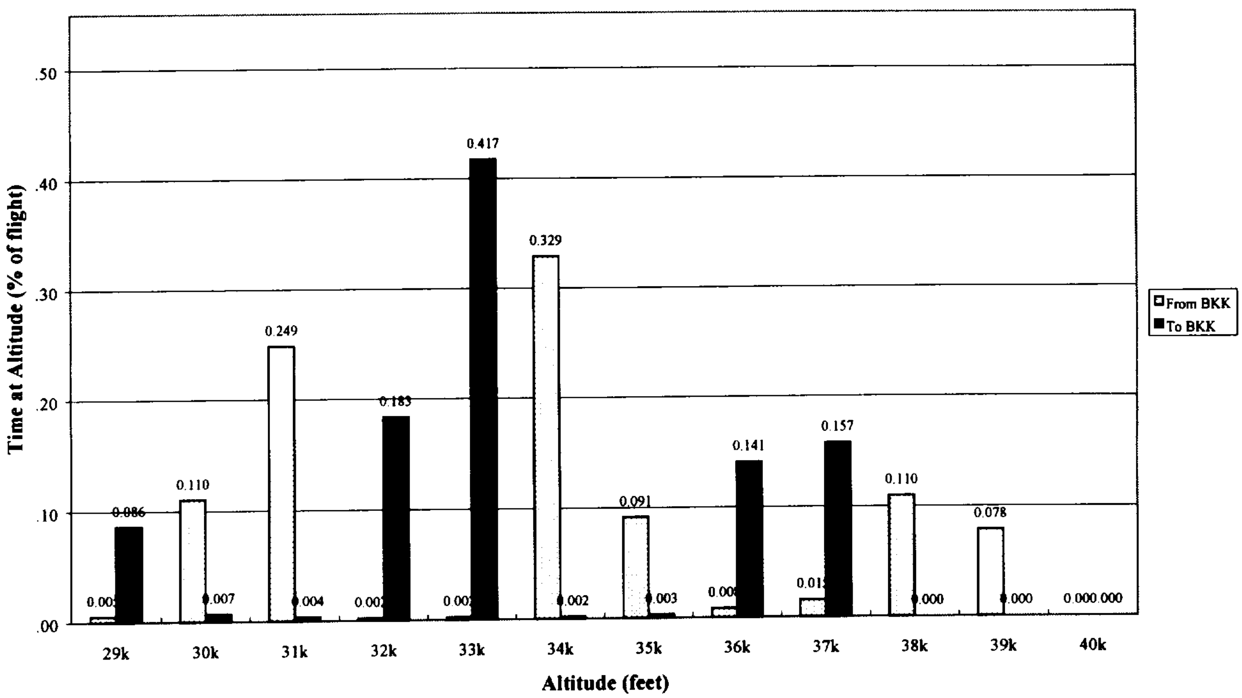
747-400 Weight @ Cruise for LHR/SIN



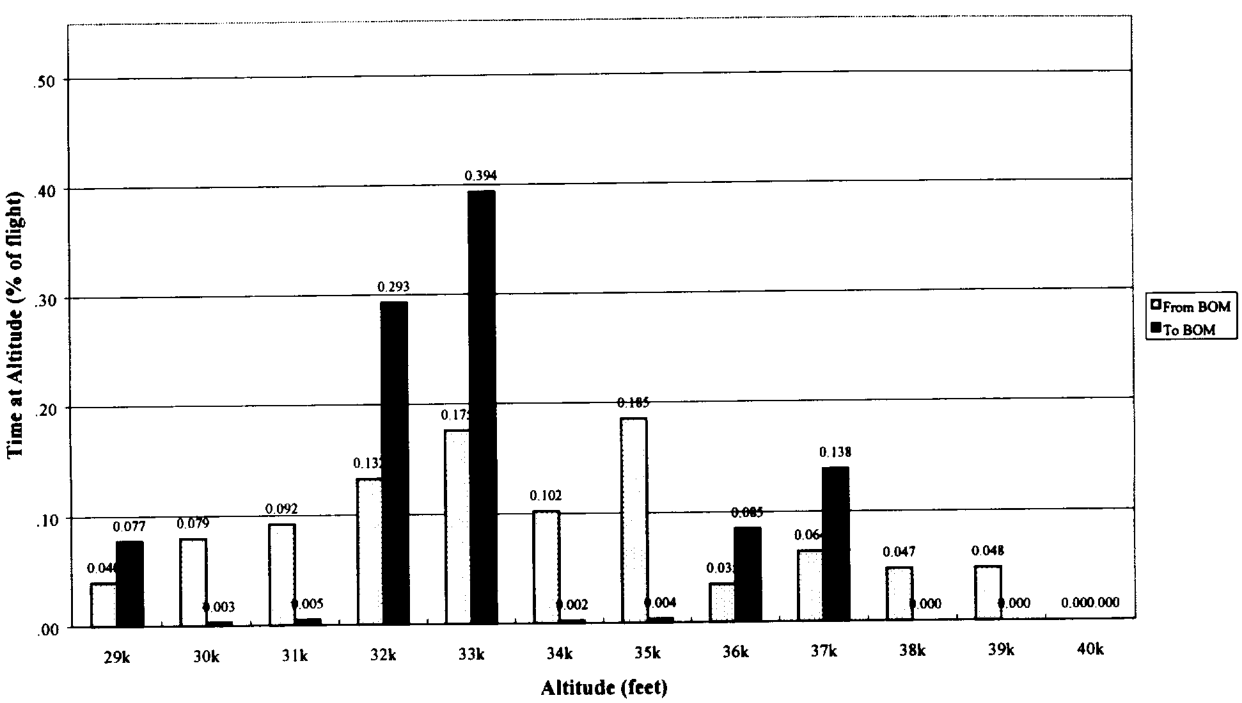
APPENDIX D -
Time at Altitude Data

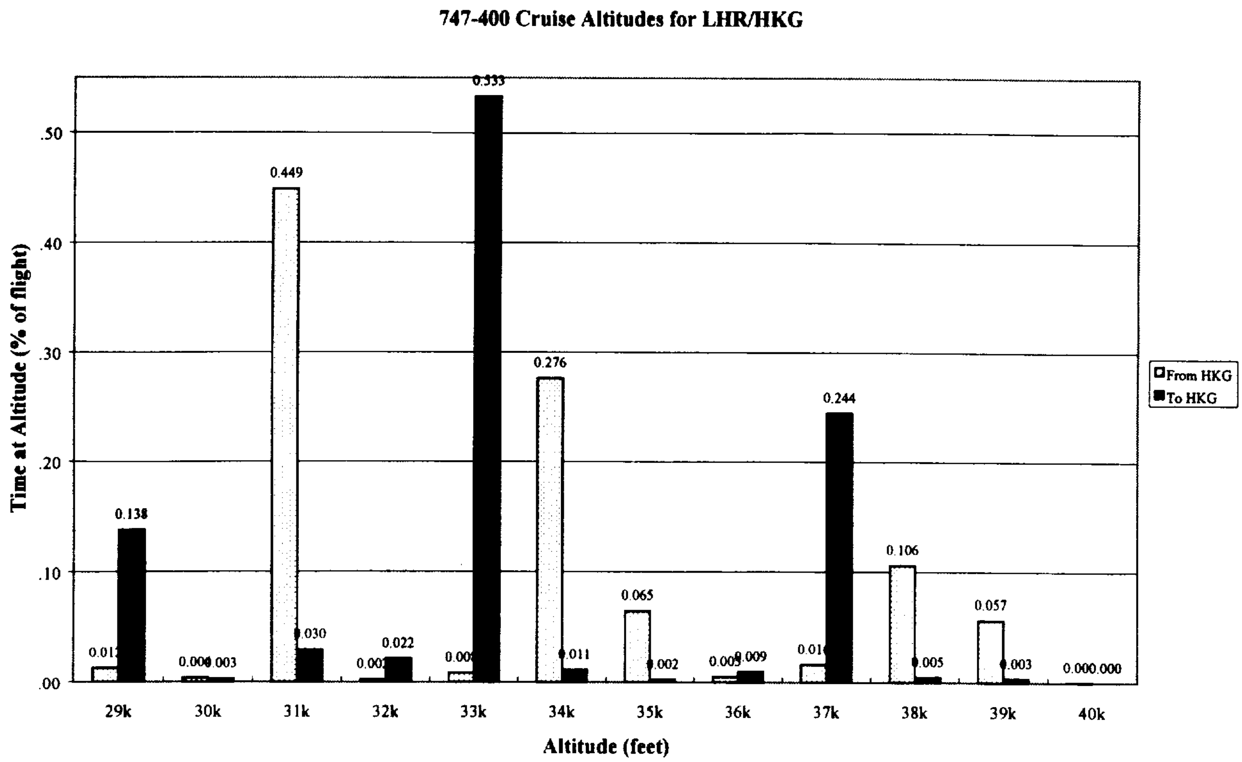
This appendix contains data on the length of time that the operator's 747-400 fleet spends at each altitude during cruise, grouped by city-pair.

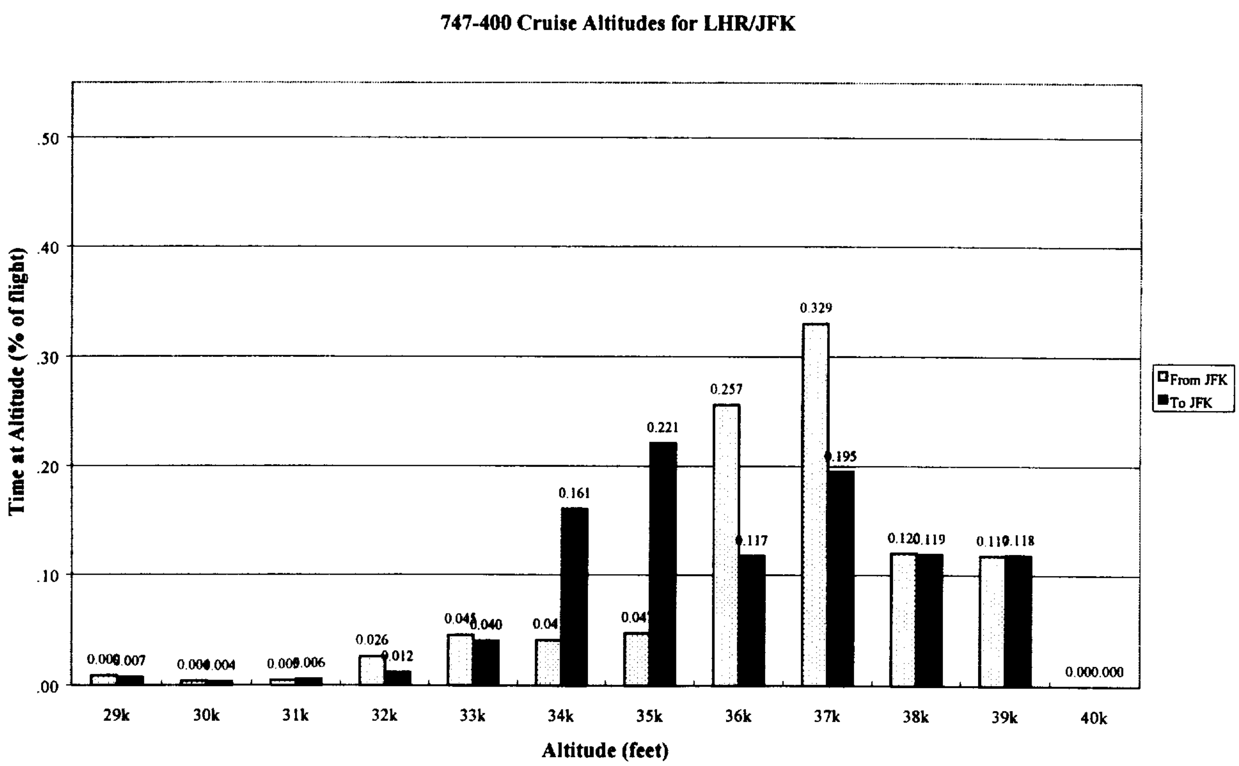
747-400 Cruise Altitudes for LHR/BKK



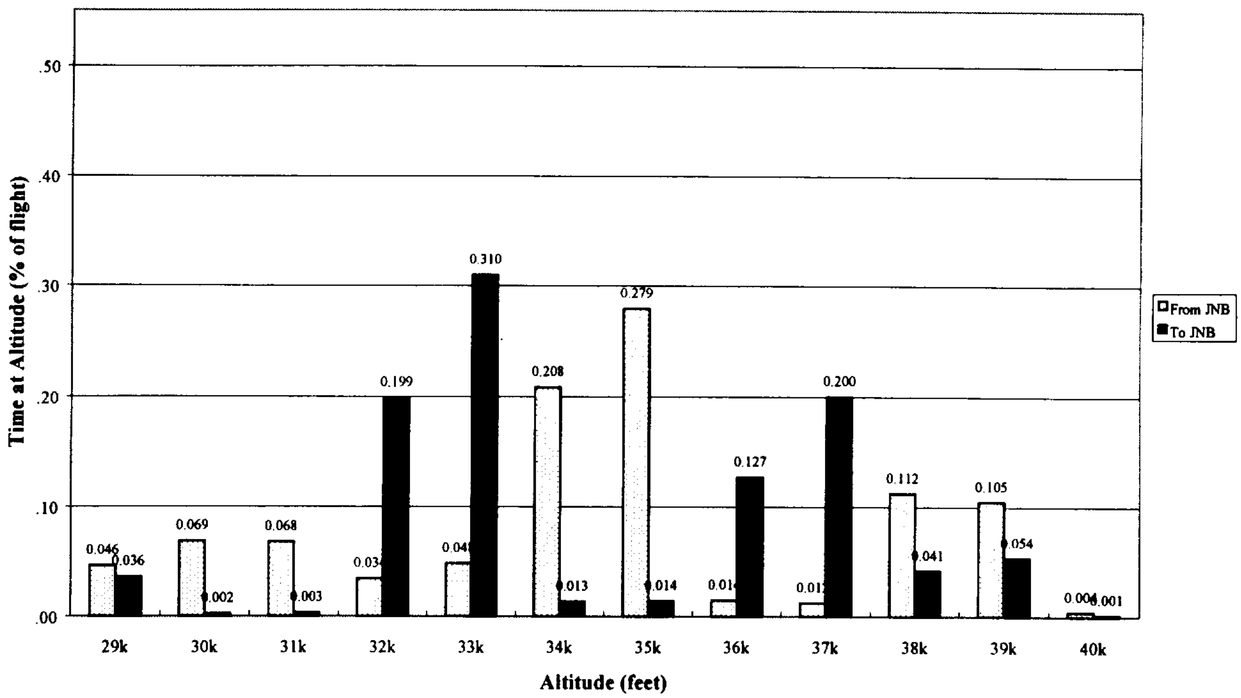
747-400 Cruise Altitudes for LHR/BOM



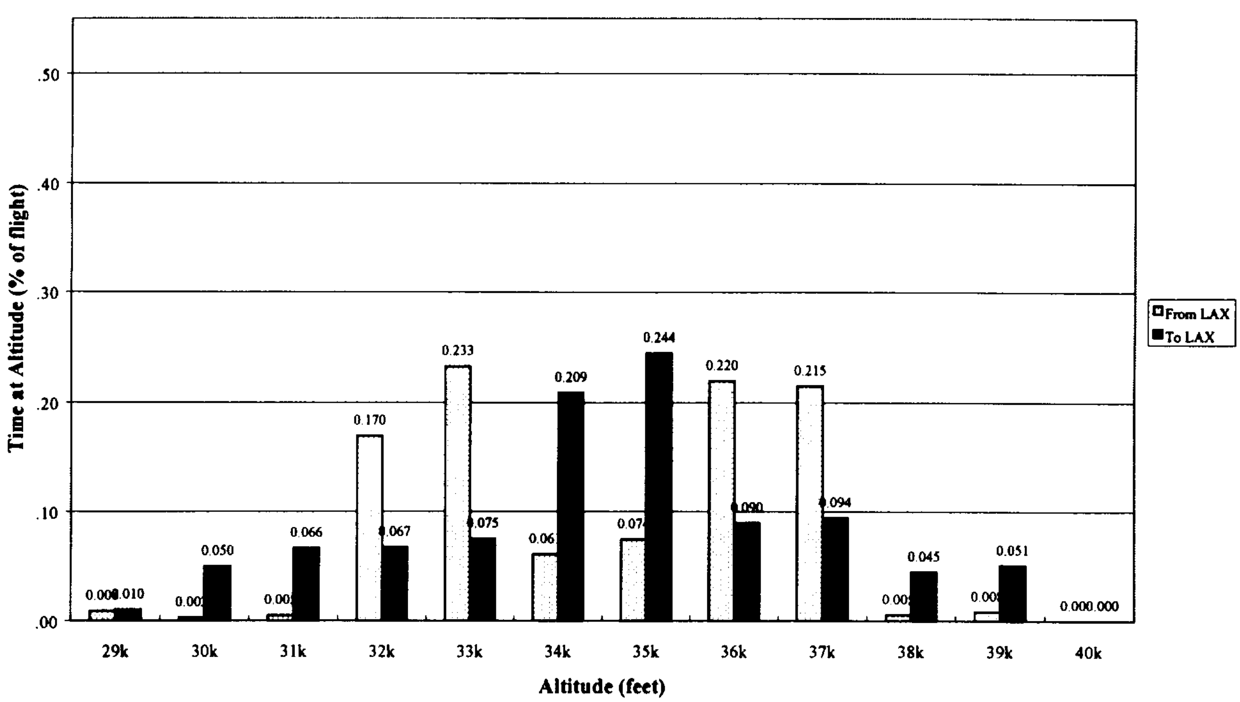

747-400 Cruise Altitudes for LHR/HKG
Time at Altitude (% of flight)
Altitude (feet)
From HKG
To HKG
0.449
0.533
0.276
0.244
0.138
0.106
0.065
0.057
0.030
0.022
0.011
0.002
0.009
0.005
0.003
0.000.000
29k
30k
31k
32k
33k
34k
35k
36k
37k
38k
39k
40k


747-400 Cruise Altitudes for LHR/JFK
Time at Altitude (% of flight)
Altitude (feet)
From JFK
To JFK
0.329
0.257
0.221
0.195
0.161
0.117
0.120.119
0.119.118
0.040
0.026
0.012
0.007
0.004
0.006
0.000.000
29k
30k
31k
32k
33k
34k
35k
36k
37k
38k
39k
40k

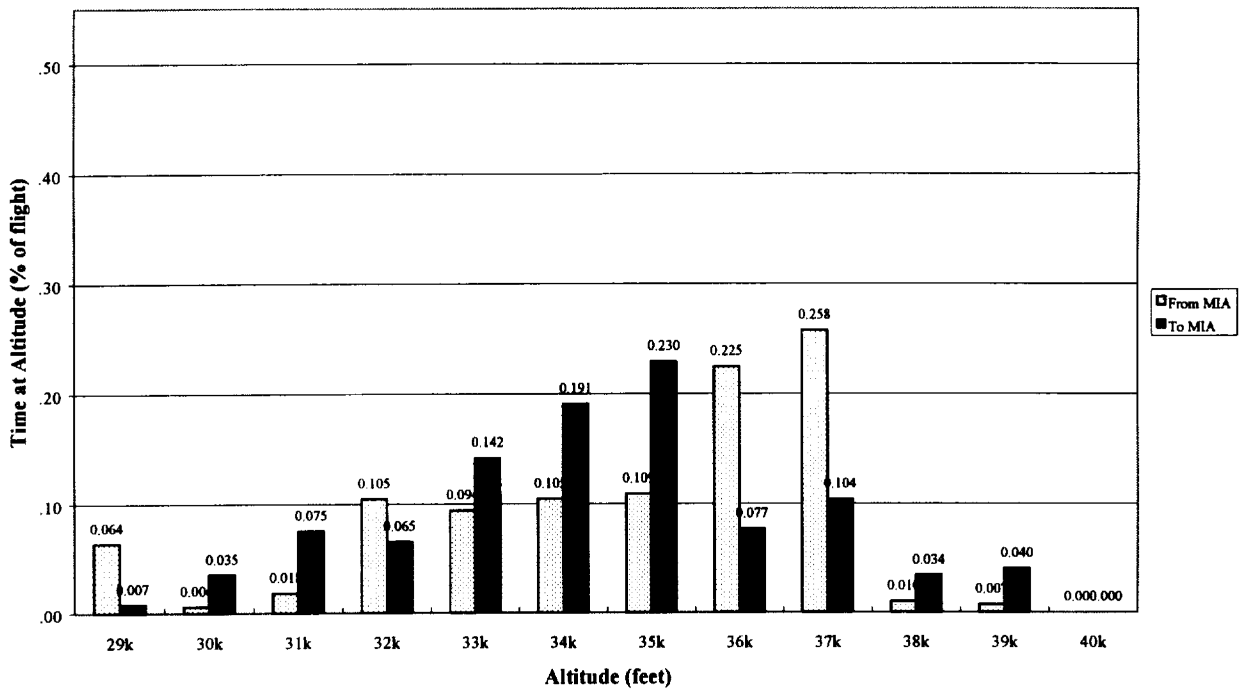
747-400 Cruise Altitudes for LHR/JNB



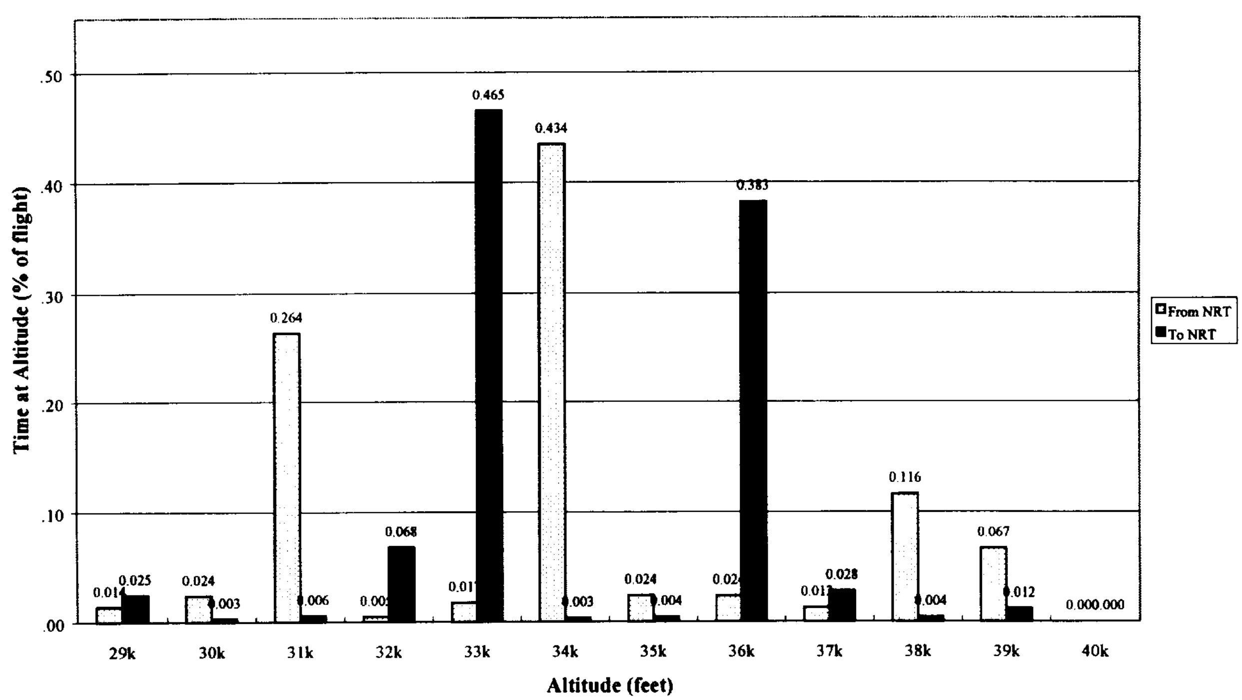
747-400 Cruise Altitudes for LHR/LAX



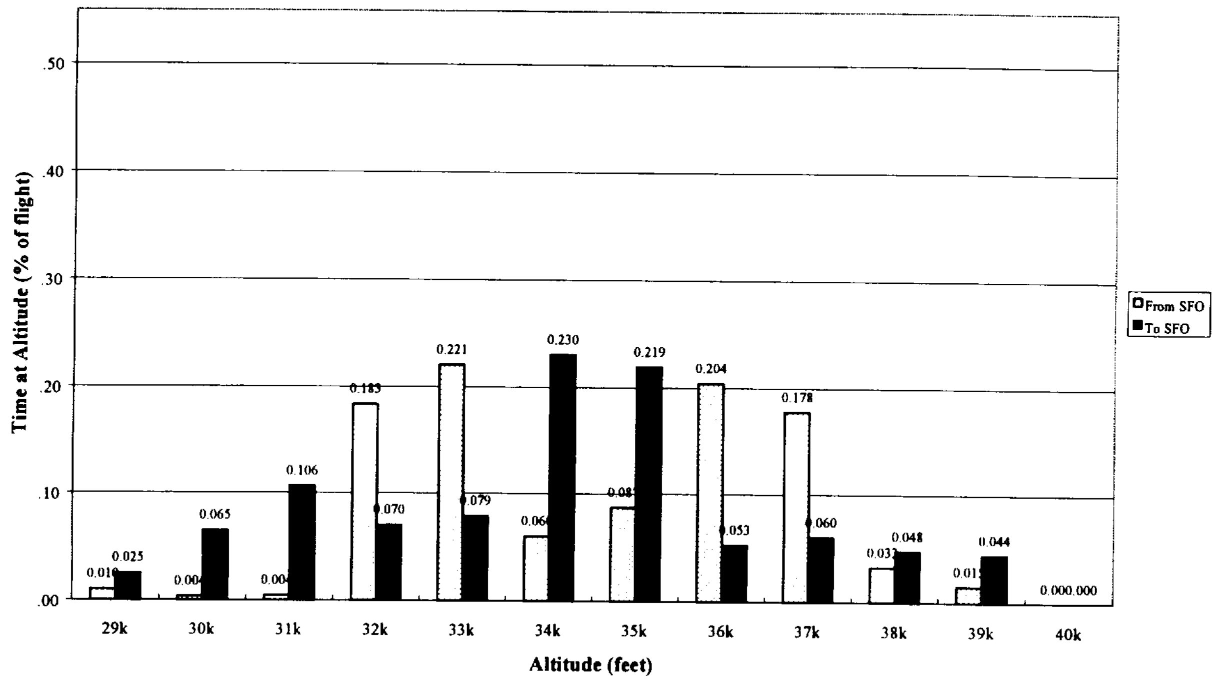
747-400 Cruise Altitudes for LHR/MIA



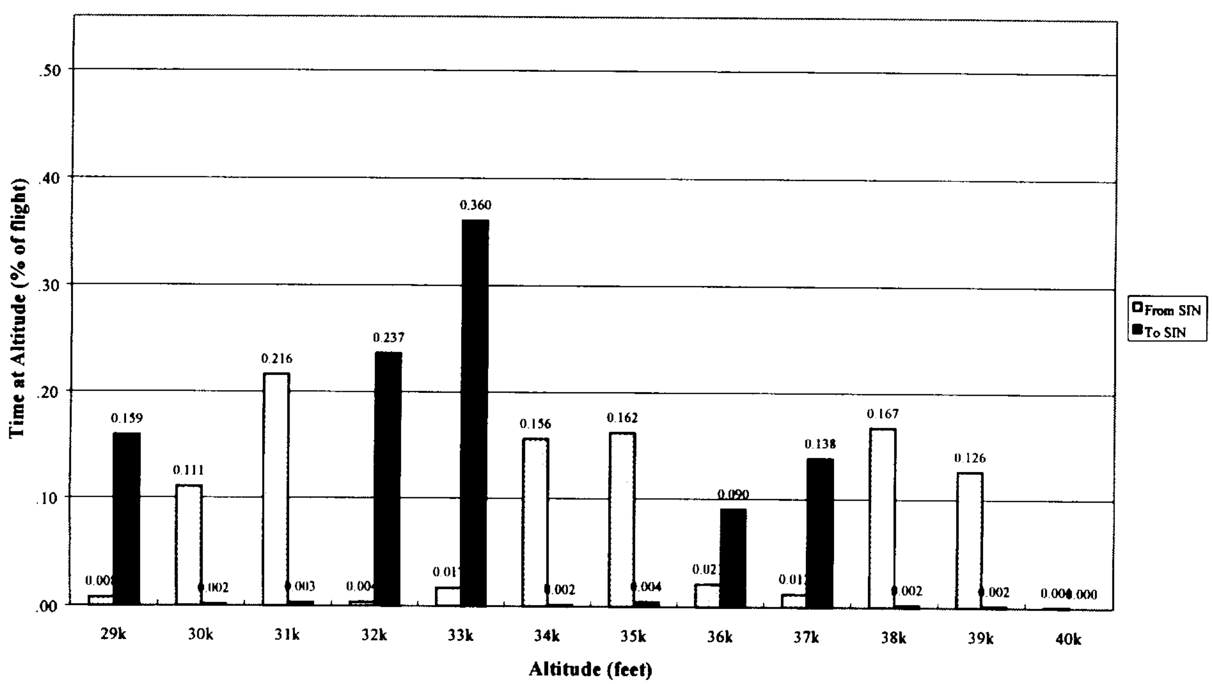
747-400 Cruise Altitudes for LHR/NRT



747-400 Cruise Altitudes for LHR/SFO



747-400 Cruise Altitudes for LHR/SIN



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13. ABSTRACT *(Maximum 200 words)*

This report provides results of work done to evaluate the calculation methodology used in generating aircraft emissions inventories. Results from the inventory calculation methodology are compared to actual fuel consumption data. Results are also presented that show the sensitivity of calculated emissions to aircraft payload factors. Comparisons of departures made, ground track miles flown and total fuel consumed by selected air carriers were made between U.S. Dept. of Transportation (DOT) Form 41 data reported for 1992 and results of simplified aircraft emissions inventory calculations. These comparisons provide an indication of the magnitude of error that may be present in aircraft emissions inventories. To determine some of the factors responsible for the errors quantified in the DOT Form 41 analysis, a comparative study of in-flight fuel flow data for a specific operator's 747-400 fleet was conducted. Fuel consumption differences between the studied aircraft and the inventory calculation results may be attributable to several factors. Among these are longer flight times, greater actual aircraft weight and performance deterioration effects for the in-service aircraft. Results of a parametric study on the variation in fuel use and NOx emissions as a function of aircraft payload for different aircraft types are also presented.

14. SUBJECT TERMS
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