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Stratospheric Emissions Effects Database Development

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Contract NAS1-19360
Prepared for Langley Research Center

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Executive Summary

This report describes the development of a stratospheric emissions effects database (SEED) of aircraft fuel burn and emissions from projected Year 2015 subsonic aircraft fleets and from projected fleets of high speed civil transports (HSCTs). These emissions inventories were developed under the NASA High Speed Research Systems Studies (HSRSS) contract NAS1-19360, Task Assignment 3. This report also describes the development of a similar database of emissions from Year 1990 scheduled commercial passenger airline and air cargo traffic, developed under the NASA HSCT Systems Studies Contract NAS1-18377, Task Assignment 11.

The objective of this work was to initiate, develop, and maintain an engineering database for use by atmospheric scientists conducting the Atmospheric Effects of Stratospheric Aircraft (AESA) modeling studies. Fuel burned and emissions of nitrogen oxides (NO_x as NO_2), carbon monoxide, and hydrocarbons (as CH_4) have been calculated on a 1 degree latitude x 1 degree longitude x 1 kilometer altitude grid and delivered to NASA as electronic files. This report describes the assumptions and methodology for the calculations and summarizes the results of these calculations.

Scenarios for Year 2015 were calculated by projecting subsonic fleet growth, aircraft technology, and engine technology. Flight frequencies for a possible fleet of 500 Mach 2.4 HSCTs in active service were calculated. A similar schedule was projected for Mach 2.0 HSCTs, assuming the same passenger demand. HSCT scenarios at two nitrogen oxide emission levels (corresponding to approximate NOx emission indices of 5 and 15 grams/kg fuel) were calculated for Mach 2.0 and Mach 2.4 aircraft. Three-dimensional distribution of emissions for projected scheduled subsonic airliner, cargo, and turboprop aircraft were then calculated for cases with and without an HSCT fleet.

Emission scenarios were calculated for the 1990 scheduled subsonic airliner, cargo, and turboprop world fleets based on the May 1990 Official Airline Guide (OAG) using engineering data available at Boeing on 58 aircraft/engine combinations. In addition, aircraft/engine characteristics were combined to produce "generic" 1990 aircraft characteristics. An emission scenario using these generic aircraft was calculated to evaluate the quality of the "generic" versus the real aircraft scenario; and it was shown that signficant errors can occur by the use of "generic" aircraft types.

Table of Contents

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Table of Contents (cont)

List of Figures

List of Figures (cont)

List of Figures (cont)

List of Figures (cont)

List of Tables

List of Tables (cont)

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1. Introduction

A major goal of the NASA High Speed Research Program (HSRP) and of the Boeing High Speed Civil Transport (HSCT) program is to design an HSCT that will not cause a significant impact on the stratospheric ozone layer. To help achieve that goal, NASA has funded the Atmospheric Effects of Stratospheric Aircraft (AESA) project to assess the impact of a fleet of commercial supersonic transports on the atmosphere. To support that assessment, Boeing and McDonnell Douglas were contracted to calculate three-dimensional inventories of emissions from fleets of HSCTs. Scenarios of projected subsonic air traffic, both with and without HSCT fleets, were also calculated for use in the atmospheric assessment. These fleets were projected for the year 2015. Emissions were also calculated for aircraft fleets in use in 1990, as a reference case.

The scenarios developed are summarized in Table 1-1. Boeing calculated emission scenarios for fleets of Mach 2.0 and Mach 2.4 HSCTs, while McDonnell Douglas analyzed Mach 1.6 HSCT fleets. Boeing calculated emission scenarios for scheduled airline, cargo, and turboprop aircraft based on schedules published in the Official Airline Guide (OAG) or projected from them. McDonnell Douglas evaluated emissions for military, charter, and other non-scheduled air traffic, including non-OAG traffic within the former Soviet Union and China.

This work is an extension of the earlier Boeing work (Reference 1) of scheduled air traffic emissions. Although the previous work projected flight schedules, the calculations of emissions were based on average fuel consumption and emissions at cruise conditions. In the new work reported here, fuel consumption and emissions of nitrogen oxides (NOx), carbon monoxide (CO), and hydrocarbons (HC) are considered for all flight segments and are reported on a three-dimensional grid with a resolution of 1 degree latitude x 1 degree longitude x 1 km altitude.

Table 1-1. Emissions Scenarios Developed for the 1993 NASA AESA Assessment. (Components of Each Scenario are Also Shown)

Scenario		Components of Scenario
A	1990 Fleet	Scheduled (OAG) airline, cargo, and turboprop; charter; military; and other (non-OAG, including internal former Soviet Union, China)
B	2015 Subsonic Fleet (without HSCTs)	Year 2015 Scheduled (OAG) airline, cargo, and turboprop; charter; military; and other (non-OAG, including internal former Soviet Union, China), assumes no HSCT fleet exists
C	2015 Mach 1.6 HSCT (EI=5)*	Scenario B with scheduled subsonic airlines revised to account for HSCTs and a fleet of Mach 1.6 HSCTs with EI=5
D	2015 Mach 1.6 HSCT (EI=15)*	Scenario B with scheduled subsonic airlines revised to account for HSCTs and a fleet of Mach 1.6 HSCTs with EI=15
E	2015 Mach 2.4 HSCT (EI=5)*	Scenario B with scheduled subsonic airlines revised to account for HSCTs and a fleet of Mach 2.4 HSCTs with EI=5
F	2015 Mach 2.4 HSCT (EI=15)*	Scenario B with scheduled subsonic airlines revised to account for HSCTs and a fleet of Mach 2.4 HSCTs with EI=15
G	2015 Mach 2.4 HSCT (EI=45)*	Scenario B with scheduled subsonic airlines revised to account for HSCTs and a fleet of Mach 2.4 HSCTs with EI=45
H	2015 Mach 2.0 HSCT (EI=5)*	Scenario B with scheduled subsonic airlines revised to account for HSCTs and a fleet of Mach 2.0 HSCTs with EI=5
I	2015 Mach 2.0 HSCT (EI=15)*	Scenario B with scheduled subsonic airlines revised to account for HSCTs and a fleet of Mach 2.0 HSCTs with EI=15

*Scheduled subsonic fleet emissions are revised to account for flights from HSCTs. Also, NO_x Emission Index (EI, in grams of NO_x as NO_2 emitted per kg of fuel) are approximate and refer to the nominal emission levels at cruise altitudes for the HSCT fleet in the scenarios; EI for subsonics will be different for each projected aircraft type. Scenario G was calculated by NASA by scaling the NOx emissions in the Mach 2.4, EI=15, HSCT data set by a factor of three, for parametric studies.

Three-dimensional (1 degree latitude x 1 degree longitude x 1 km altitude) distributions of fuel burned, nitrogen oxides (NO_X), carbon monoxide (CO), and hydrocarbons (HC) were calculated by Boeing for the following:

- 1990 scheduled airliner, cargo, and turboprop aircraft
- Projected 2015 scheduled subsonic airliners (assuming no HSCT fleet exists)
- Projected 2015 scheduled subsonic airliners (assuming an HSCT fleet of 500 Mach 2.4 HSCTs were flying)
- Projected 2015 scheduled cargo aircraft
- Projected 2015 scheduled turboprop aircraft
- Projected 2015 HSCT traffic for 500 Mach 2.4 HSCTs with nominal NO_X emission indices of 5 and 15 gm NO_X/kg fuel burned at cruise.
- Projected 2015 HSCT traffic for 500 Mach 2.0 HSCTs with nominal NO_X emission indices of 5 and 15 gm NO_X/kg fuel burned at cruise.

Given the fuel burned in each grid cell, emissions of water vapor, carbon dioxide, and sulfur dioxide can be determined from the fuel properties.

The emissions computation process is shown schematically in Figure 1-1. In order to generate the emissions for each scenario, it is necessary to account for the aircraft performance, engine performance and emission characteristics, and market data of traffic projections, flight frequencies, city-pairs, and routing. These inputs are combined to calculate the mission profiles of fuel burned and emissions which are then projected onto the latitude x longitude x altitude grid. Mission profiles are calculated based on performance. The flight altitude of an HSCT will vary with its cruise Mach number, increasing with higher speeds. The cruise altitude will also increase during the flight as fuel is burned and the aircraft becomes lighter. The details of this process are described in this report.

This report documents the assumptions, methods, and results used in the scenarios developed for the 1993 NASA HSRP interim assessment. Many of the ground rules and some of the details have been described earlier in annual reports of the AESA program (References 2-4) and will be discussed in more depth later in this report.

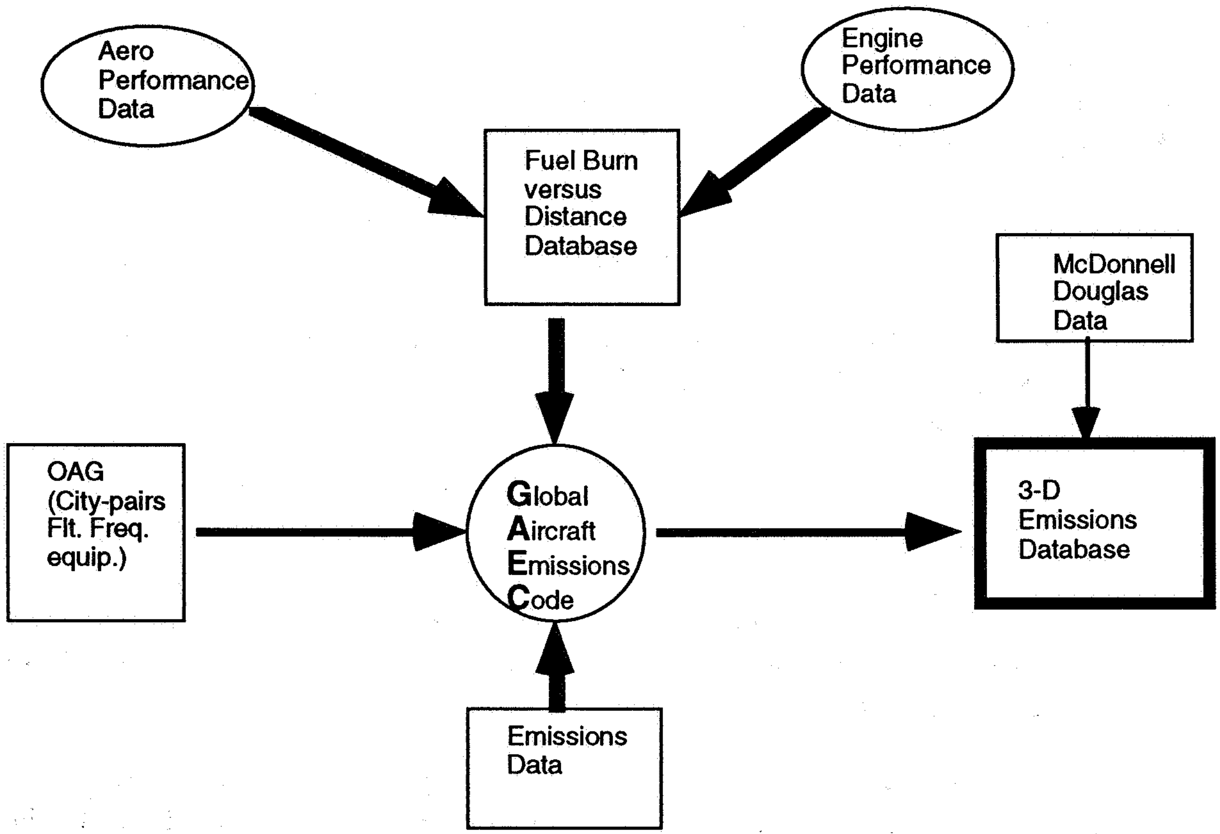


Figure 1-1. Schematic of emission scenario calculation process

The work on HSCT and Year 2015 emission scenarios described in this report has been conducted under NASA Langley Contract NAS1-19360, Task 3. The work on 1990 emission scenarios was funded under NASA Langley Contract NAS1-18377, Task 11. The NASA Langley Task Manager was Donald L. Maiden.

Within the Boeing HSCT engineering group, overall program management was provided by Malcolm I. K. MacKinnon, John D. Vachal, and John H. Gerstle. The principal investigator of the task was Steven L. Baughcum. Chief contributors were Stephen C. Henderson, Terry Higman, Thomas T. Odell, and Richard Bateman in market analysis; Dik M. Chan in HSCT performance analysis; Stephen M. Happenny in HSCT propulsion; Carlos A. Oncina in subsonic propulsion; Peter S. Hertel in computer support; and Debra R. Maggiora in data analysis.

2. Year 2015 Market Forecast

2.1 Total Passenger Demand

The passenger demand, which forms the basis of the year 2015 route system emissions analysis, was done in cooperation with McDonnell Douglas. Data regarding growth rate forecasts were exchanged, and a single growth scenario was devised which resulted in a common forecast for passenger demand. Both companies produce passenger demand projections as part of normal business activity. (References 5-6) These projections were used as each company's submittal to create the common forecast.

After exchanging forecast growth rate data, Boeing and McDonnell Douglas agreed that a simple averaging of growth rates by regional market would suffice to create a common forecast. Table 2-1 shows the McDonnell Douglas forecast (Reference 6), the Boeing forecast (Reference 5), and the common forecast used in the analysis.

Table 2-1. Annual Growth Rates (as percent) in Scheduled Passenger Demand Determined by Boeing and McDonnell Douglas.

	Passenger Demand Growth Rate Percentage							
	McDonnell Douglas	Boeing			"Common" Rates			
From (Year)	1990	1990	2000	2005	1990	2000	2005	2010
To (Year)	2000	2000	2005	2010	2000	2005	2010	2015
Region:								
North America - Europe	5.0	5.1	4.3	4.2	5.0	4.2	4.1	4.0
North America - Asia	11.7	8.5	7.4	7.2	10.1	8.8	8.6	8.0
North America - Latin America	6.6	6.5	5.0	5.0	6.6	5.1	5.1	5.0
Europe - Asia	8.4	8.8	7.8	7.3	8.6	7.6	7.1	7.0
Intra Asia	10.7	8.1	7.2	7.0	9.4	8.4	8.1	8.0

The revenue passenger miles were projected to year 2015 using the average annual growth rates obtained from this common forecast. These are summarized below in Table 2-2 for different regions.

Table 2-2. Projected growth in revenue passenger miles (RPMs) from 1991 to 2015 using the common annual growth rate

Region	1991 RPMs (millions)	"common" Annual Growth Rate	2015 RPMs (millions)
Domestic United States/Canada and US-Canada	355682	5.13%	1181686
North America-Europe	115080	4.50%	330972
North America- Asia	79080	9.10%	639531
North America- Middle East	3444	4.50%	9906
North America -Latin America*	35744	5.70%	135208
Intra Europe	97208	4.50%	279572
Asia - Europe	26403	7.80%	160140
India Subcontinent- Europe	10065	3.90%	25210
Middle East - Europe	16557	3.90%	41472
Africa - Europe	22216	6.67%	104638
Latin America - Europe	24111	4.50%	69345
Intra Asia	85260	8.70%	631325
Asia-Africa	16443	8.70%	121755
Domestic Japan	32849	4.50%	94474
Domestic India Subcontinent	7670	8.70%	56794
India Subcontinent- Middle East	10713	8.70%	79325
Domestic Middle East	13684	4.50%	39354
Domestic Africa	9932	4.50%	28565
Domestic Latin America	27951	8.90%	216305
People's Republic of China- International	9678	9.10%	78267
Former Soviet Union - International	12199	4.50%	35084
Total	1011969		4358928

*Latin America = Central America + South America + Caribbean

2.2 HSCT Passenger Market Forecast

Because supersonic booms will likely be unacceptable for flights over land, the HSCT is expected to fly supersonically only over water. While subsonic flights over land would be permitted, it is expected that they would be minimized in order to get the maximum productivity from the HSCT. Some subsonic flights would occur in order to position the aircraft between viable intercontinental cities. Using these assumptions and the growth projections described above, the HSCT demand network was developed using the following ground rules:

- No supersonic flight over land;
- Flight distances must be greater than 2000 nautical miles;
- No more than 50% of the flight distance routed over land (i.e, >50% of flight distance flown supersonically)
- Flight paths could be altered using waypoints to avoid flying over land but with no more than 20% diversion from great circle routing;
- Great circle paths would be flown between waypoints.
- Passenger demand between two HSCT city pairs must be able to support 1 flight/day at 70% load factor in 2015.

These ground rules were developed between Boeing and McDonnell Douglas and represent a consensus on the requirements to be met for viable HSCT service. Based on these ground rules, a set of candidate city-pairs and route paths was developed. A single set of city-pairs and flight frequencies was agreed upon which met the ground rules described above and met the further requirement that the HSCT route system would need about 500 active Mach 2.4 HSCTs with 300 seat capacity to meet the passenger demand.

Using the common projections to 2015, the relative HSCT passenger demand by region is shown in Figure 2-1. The North

America-Asia and North America-Europe markets are predicted to dominate.

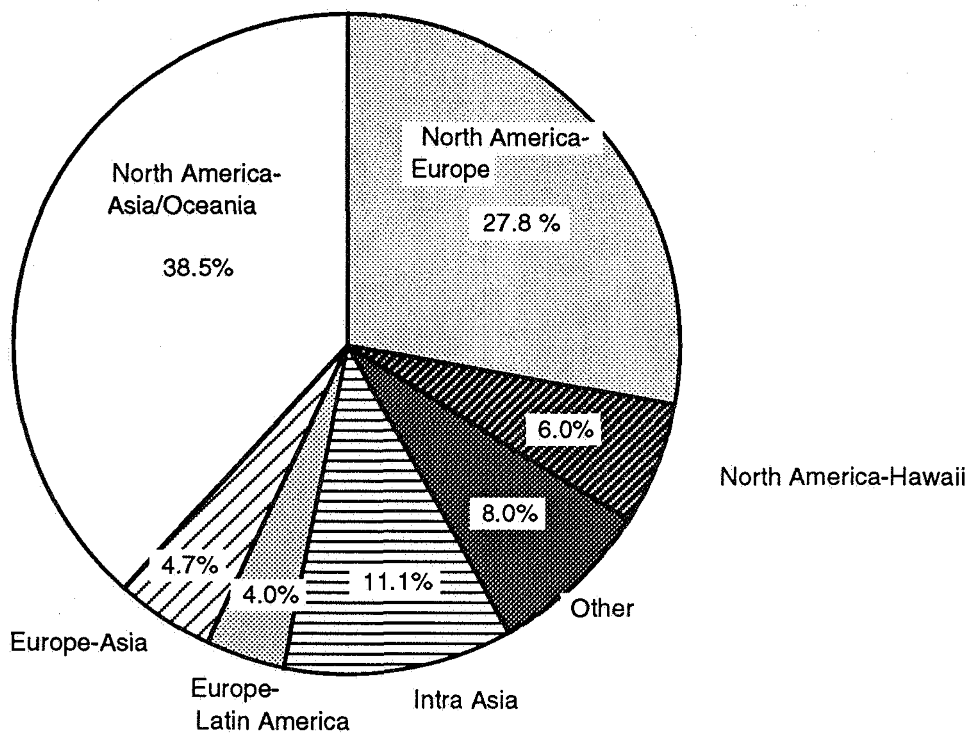


Figure 2-1. Distribution of HSCT passenger demand by region.

2.3 HSCT Routing and Frequencies

The passenger demand estimate for the year 2015 was partitioned between the different city-pairs to create a single universal airline network. Flights were scheduled to satisfy local airport curfews. The HSCT network was then developed as follows:

- Equal penetration assumed in all markets.
- City-pairs unable to support at least one HSCT flight per day with at least 70% of load capacity in 2015 were allocated to the subsonic fleet and dropped from the HSCT network.
- HSCT aircraft were then allocated to maximize the utilization of 500 Mach 2.4 HSCTs.

- One hour through times (flights with refueling stops) and 1.5 hour turnaround times were assumed.

For Mach 1.6 and Mach 2.0, flights were scheduled to maintain the same passenger demands as for the Mach 2.4 HSCT. The results are summarized for different HSCTs and for the subsonic aircraft they replace in Table 2-3

Table 2-3. HSCT Network Analysis

	Mach Number			
	0.84	**1.6**	**2.0**	**2.4**
Passengers/Day	386,224	386,778	386,778	386,778
Seats	300	300	300	300
Load Factor (%)	69.6	70.0	70.0	70.0
Units Required	961	594	532	500
Daily Utilization (hours)	17.0	17.2	16.6	16.3
ASM/Year (Billions)	809.6	830.8	830.8	830.8

The HSCT fleet would carry 387,000 people/day, with an average load factor of 70%. The average stage length was 3400 nautical miles with an average diversion from great circle routing of 4.2%. Based on these assumptions of high utilization, the HSCT would achieve a market penetration of 48% on these routes. These high utilization rates are consistent with the scheduling guidelines; and they probably represent an upper limit utilization for 500 Mach 2.4 HSCTs in active service.

The higher speed aircraft would be able to fly more trips and thereby carry more people per day per aircraft. A larger number of HSCTs would be required for slower aircraft to meet the same passenger demand. These calculations result in a Mach 2.4 HSCT active fleet flying 16.3 hours/day, while the Mach 1.6 HSCT fleet would be used, on average, about 17.2 hours per day. While 500 active Mach 2.4 aircraft are required to carry all the passengers, 532 active Mach 2.0 or 594 active Mach 1.6 HSCTs would be required to meet the same passenger demand. The average total fleet utilization would likely be somewhat lower than this as additional aircraft would be needed for replacement aircraft during periodic maintenance, etc.

The HSCT emissions study departure network is graphically depicted in Figure 2-2. Appendix A contains a list of the HSCT city pair codes and identifies the cities. Details of the network are included in Appendices B and C. Appendix B lists origin, destination, and "via" cities (refueling stops required when the origin-destination distance is greater than the 5000 nautical mile nominal range for the HSCT designs now contemplated). Also listed are flights per day and the great circle paths and the HSCT flight-path distances between cities. Since it was assumed for this study that supersonic flight over land will be prohibited, the HSCT flight path distances are greater than the great circle paths due to the routings that have been defined to avoid supersonic flight overland and to minimize subsonic overland flight. This resulted in HSCT service between 199 city-pairs. Because some HSCT flights are routed through the same cities, 386 mission profiles were calculated to fly this network. Appendix C contains a list of the departures and the waypoint routing used to avoid supersonic flights overland.

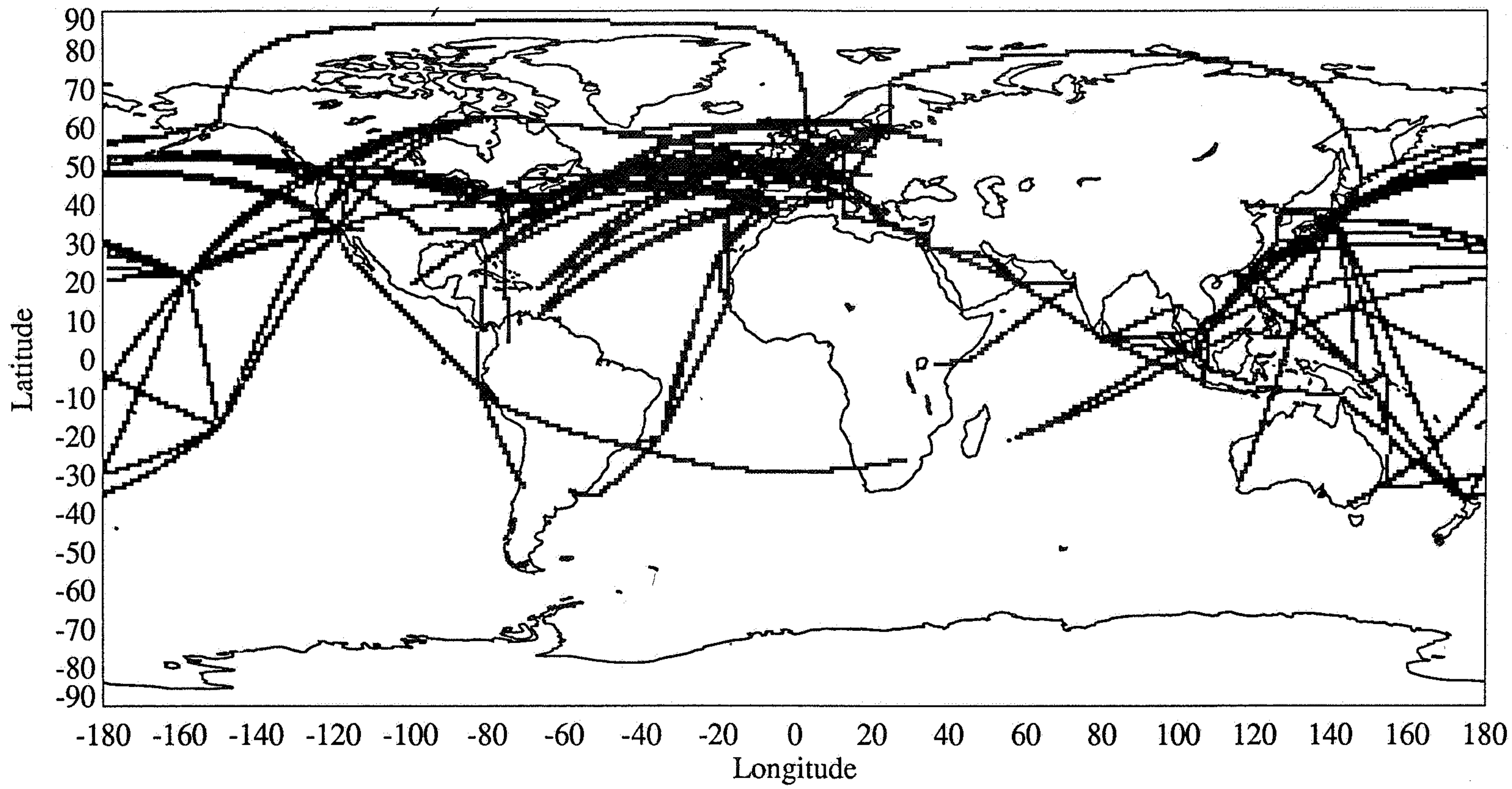


Figure 2-2. HSCT Route System for the Year 2015

Flight Path Routing to Minimize Flight Over Land - An Example

Flying the shortest (great circle) flight path between the cities in the HSCT route system results in a large percentage (>50%) of the total system flight path occurring over land (and at subsonic speeds). Altering the flight path to attempt to minimize overland flight can greatly reduce the percentage of overland flight with a small penalty in total distance flown.

As an example, consider flights from Frankfurt (FRA) to Bangkok (BKK). The shortest (great circle) flight path is 4841 nautical miles, all over land and hence would be flown subsonically. The flight path between FRA and BKK was altered by using "waypoints", defined latitude-longitude positions that the HSCT is required to fly over. (The airplane flies a great circle path between the waypoints). As shown in Figure 2-3, the waypoints route the HSCT flight path subsonically from Frankfurt to near Venice, then supersonically down the Adriatic, across the Mediterranean to the Sinai, with a direct path across the Arabian peninsula, around India to Bangkok. As illustrated in Table 2-4, this path, although reducing the amount of subsonic flight over land to 1862 nautical miles, exceeds the 5000 nautical mile design range of the present HSCT configurations. The flight path must be modified to include a stop at Bahrain to refuel (and pick up passengers). After a stop at Bahrain, the HSCT resumes the flight path defined above. The supersonic (more efficient) flight mode is increased from zero to 4319 nautical miles for a 28% increase in total miles flown, including a stop.

Table 2-4. Example of waypoint routing

Route Segment	Great Circle Distance (nmi)	Path Distance (nmi)	Over Water Distance (nmi)	Over Land Distance (nmi)
Frankfurt - Bangkok (Great Circle Route)	4841	4841	0	4841
HSCT Waypoint Routing Route:		6180	4319	1862
Frankfurt - Bahrain (with waypoints)	2397	2720	1396	1324
Bahrain - Bangkok (with waypoints)	2895	3460	2923	538

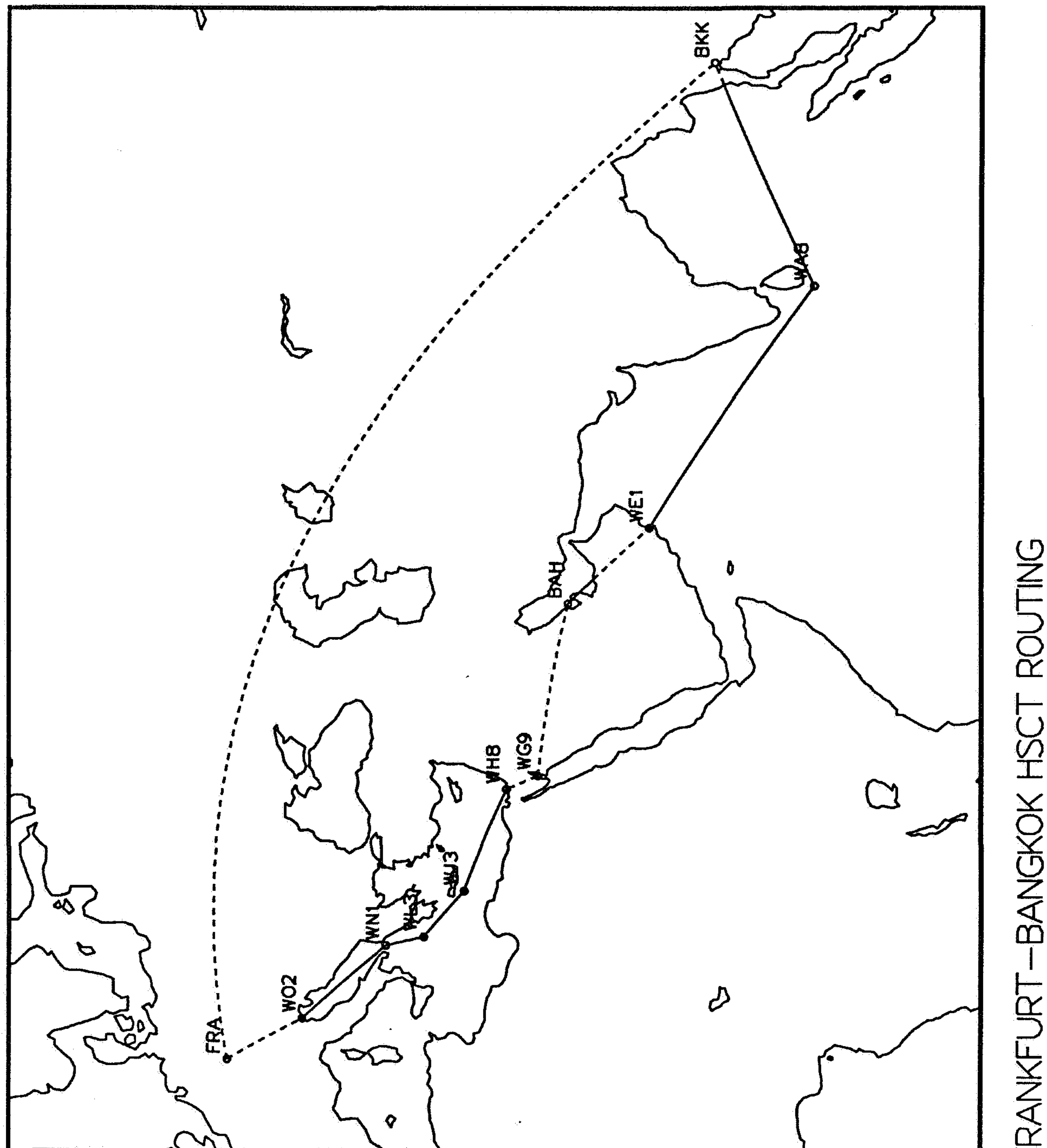


Figure 2-3. Waypoint routing example, Frankfurt - Bangkok.

Each city-pair routing, including "via" cities, was examined to determine the best waypoint-guided path to minimize overland subsonic flying. This work was simplified by using as a base a set of waypoints and routings developed within the International Working Group. These routings were modified to some extent, and many other city-pairs and routings added to create the final HSCT route system with each city-pair flight path routed by hand for maximum supersonic cruise. Figure 2-2 shows an overview of the HSCT route network, with all the waypoint-guided flight paths shown.

3. Emissions Calculation Methodology

3.1 Overview of Emissions Calculation

The primary emissions from aircraft engines are water vapor (H_2O) and carbon dioxide (CO_2) produced by the combustion of jet fuel. Nitrogen oxides (NOx), carbon monoxide (CO) and hydrocarbons are also produced in the combustors and vary in quantity according to the temperature, pressure, and other combustor conditions. Nitrogen oxides consist of both nitric oxide (NO) and nitrogen dioxides (NO_2). Sulfur dioxide may also be produced due to sulfur impurities in jet fuel. Soot is also produced, particularly at high power settings, but its characterization is beyond the scope of the current work.

The emission levels from aircraft engines are discussed by Miake-Lye (Reference 7). The emissions are characterized in terms of an emission index in units of grams of emission per kilogram of fuel burned. For NOx, the emission index [EI(NOx)] is given as gram equivalent NO_2 to avoid ambiguity. Although hydrocarbon measurements of aircraft emissions by species have been made (Reference 8), only total hydrocarbon emissions are considered in this work, with the hydrocarbon emission index [EI(HC)] given as equivalent methane (CH_4).

Nitrogen oxides are produced in the high temperature regions of the combustor primarily through the thermal dissociation of oxygen followed by oxygen atom reactions with molecular nitrogen. Thus, the NOx produced by an aircraft engine is sensitive to the length of the combustor, the pressure, and the temperature within the combustor. The emissions vary with the power setting of the engine, being highest at high thrust conditions. By contrast, carbon monoxide and hydrocarbon emissions are highest at low power settings where the temperature of the engine is low and incomplete combustion occurs.

Emission indices of NOx, CO, and hydrocarbons for commercial aircraft engines are measured at four power settings (7%, 30%, 85%, and 100%), corresponding to idle, approach, climbout and take-off, as part of their certification by the International Civil Aviation Organization (ICAO) and the Federal Aviation Administration (FAA). These four data points of measured emissions are used as the basis for the calculation of the emissions as a function of fuel flow rate. This is described in more detail below.

Once a schedule of city-pairs and departures has been determined, the next step in the development of the scenario data set is to use aircraft/engine performance and emissions data to calculate the fuel use and emissions as a function of altitude and location. For each mission, fuel consumption and emissions are calculated including all the flight segments (taxi out, takeoff, climb, cruise, descent, landing, taxi in), distributing the emissions as a function of space along the route between city-pairs. The emissions are then combined for all flights into the resulting three-dimensional database.

3.2 Subsonic Emissions Methodology

3.2.1 Engine Manufacturer's Methodology

The process for calculating aircraft engine emissions of hydrocarbon (HC), carbon monoxide (CO) and nitrogen oxides (NOx) for airplane missions requires three sources of information: engine emission information as contained in the ICAO emission databank, engine performance data as provided by engine thermodynamic cycle models, and airplane performance data. Using the thermodynamic cycle data, the combustor inlet temperature (T3) and pressure (P3) can be calculated at different flight altitudes, Mach numbers, and for different thrust conditions with installation effects. The engine companies have developed equations to calculate the emission levels from T3 and P3. (e.g., Reference 9).

Since aircraft emission measurements are generally made at static sea level conditions, scaling relationships have been developed to account for the temperature and pressure changes which would occur at flight altitudes. (e.g., Reference 10)

The following equations which require knowledge of the combustor inlet temperature (T_3) and pressure (P_3) are used by Boeing to scale emissions from the sea level test conditions to altitude:

For constant combustor inlet temperature (T_3):

$$EICO = EICO_{sl} * (P_{3sl}/P_3)$$

$$EIHC = EIHC_{sl} * (P_{3sl}/P_3)$$

$$EINOx = EINOx_{sl} * (P_3/P_{3sl})^{0.5} * e^{(-19(\omega-0.0063))}$$

where

EICO	=	carbon monoxide (CO) emission index at altitude
EIHC	=	hydrocarbon (HC) emission index at altitude
EINOx	=	NOx emission index at altitude
$EICO_{sl}$	=	CO emission index at sea level conditions
$EIHC_{sl}$	=	HC emission index at sea level conditions
$EINOx_{sl}$	=	NOx emission index at sea level conditions
P_{3sl}	=	combustor inlet pressure at sea level conditions
P_{3alt}	=	combustor inlet pressure at altitude
ω	=	specific humidity in lbs of water/lbs of air at altitude

The equations employ the correlations developed for ambient test site corrections to correct for altitude.

Using these relationships and the dependence of NOx on T3 for each engine, emission levels could be calculated from the thermodynamic cycle analysis. This will not be discussed here, since such a method is too computationally complex to be appropriate for the calculation of a global inventory of aircraft emissions. The simplified approach used in this study is described below.

3.2.2 Methodology Used for Global Emissions Database

A methodology has been developed at Boeing which correlates the emission levels and the fuel flow rates based on the equations in section 3.2.1. (Joe Zeeben, private communication). Since the fuel flow rate is normally calculated as part of aircraft/engine performance data, this provides a simple way to calculate emissions which can be implemented into a global inventory analysis.

In this method, the fuel flow rate during a mission segment is calculated from performance data. The emission index at sea level conditions (REI) at this fuel flow rate is then calculated using the measured emission indices reported to ICAO at four power settings (fuel flow rates) and interpolating to the calculated fuel flow rate. The emission idex (EI) at altitude is then calculated by scaling for ambient temperature and pressure effects.

The methodology uses the following equations for constant fuel flow factor ($W_f/\Theta^{1.5}$) :

$$EICO = REICO/\delta^{0.4}$$

$$EIHC = REIHC/\delta^{0.4}$$

$$EINOx = REINOx * \Theta * e^{(-19(\omega-0.0063))}$$

where

EICO	=	carbon monoxide (CO) emission index at altitude
EIHC	=	hydrocarbon (HC) emission index at altitude
EINOx	=	NOx emission index at altitude
REICO	=	referenced CO emission index at sea level conditions
REIHC	=	referenced HC emission index at sea level conditions
REINOx	=	referenced NOx emission index at sea level conditions

Θ = $T_{amb}/518.67$

δ = $P_{amb}/14.696$

T_{amb} = ambient temperature in degrees Rankine

P_{amb} = ambient pressure in pounds per square inch absolute

ω = specific humidity in lbs of water/lbs of air at altitude

W_f = fuel flow (kg/hour)

fuel flow parameter = $W_f/\Theta^{1.5}$

The exponents of δ and Θ were chosen solely for their ability to collapse the data. Figures 3-1 to 3-3 show the emissions results for one particular engine, where REI is plotted as a function of the fuel flow factor. The calculated data depicted were generated with the aid of an engine thermodynamic cycle deck over a range of altitudes and flight conditions. Temperature and pressure profiles from a 1976 US Standard Atmosphere were used. Superimposed on the plots are the four measured data points corresponding to the ICAO power settings. When plotted as a log versus log plot, a correlation is reached which is adequate for scenario calculations. If data at more conditions than the ICAO certification measured power settings were available, particularly at altitude and low power, a more detailed analysis might be warranted.

Note that at sea level standard conditions, the emission index is equal to the referenced emission index. The ICAO W_f is scaled for installation effects.

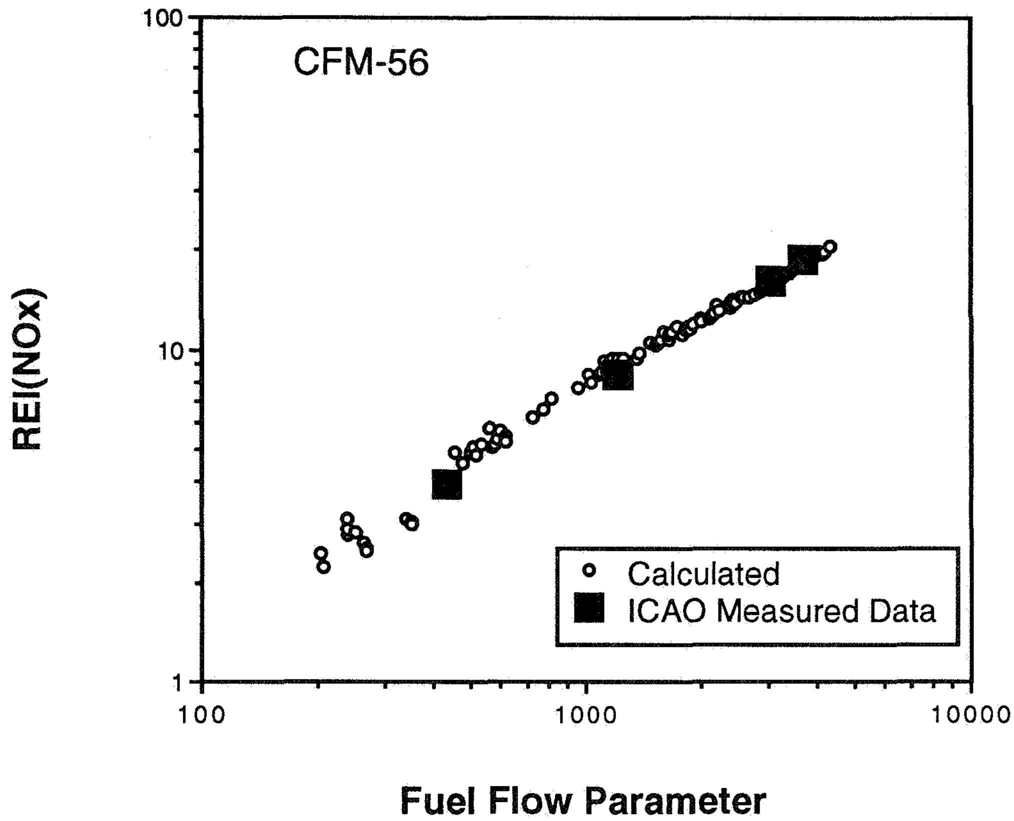


Figure 3-1. The referenced emission index (REI) for NOx as a function of fuel flow parameter for the CFM-56 engine. Both measured ICAO data and emission indices calculated using thermodynamic cycle data are shown.

The NOx emission index increases with increasing fuel flow (see Figure 3-1). The correlation is monotonic and the interpolation between fuel flow points is straightforward.

For hydrocarbons and carbon monoxide, emissions drop off dramatically at higher fuel flow rates (i.e., higher thrusts). (see Figures 3-2 and 3-3). The emission indices plateau at higher power settings, particularly for CO.

In order to calculate total flight emissions the data must be corrected for the installation effects on fuel flow. While different approaches could be taken to accomplish this, for these scenarios knowledge of the true installation effects were used.

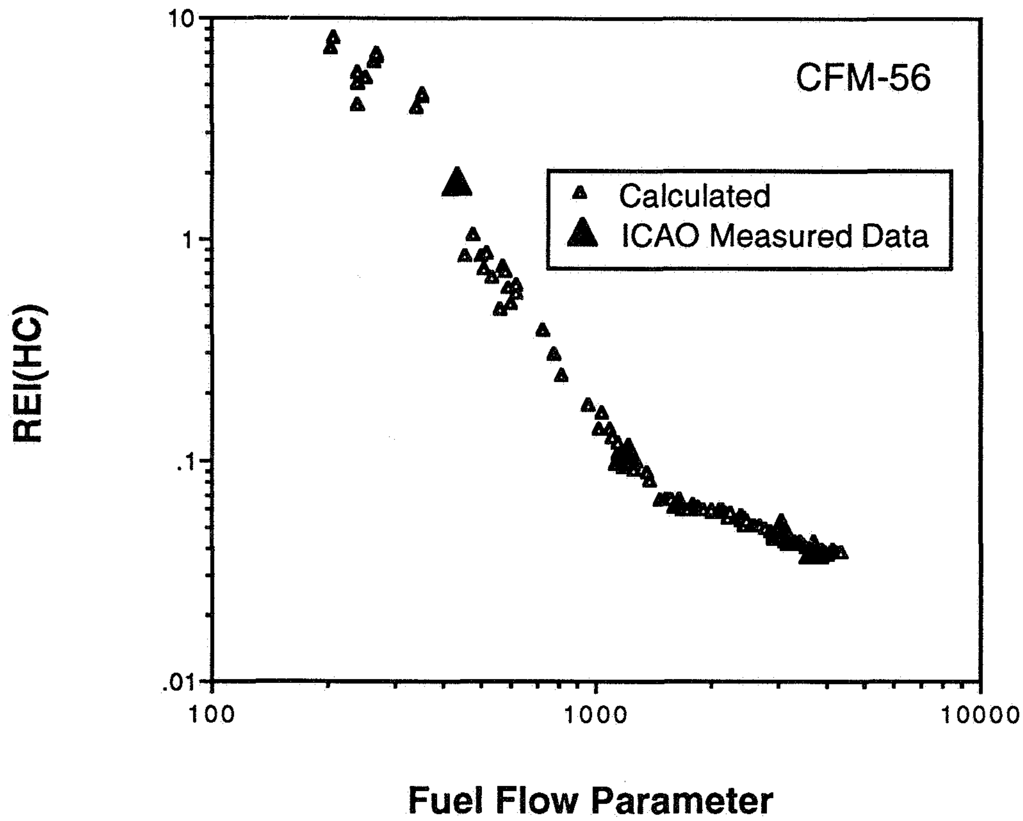


Figure 3-2. The referenced emission index (REI) for hydrocarbons as a function of fuel flow parameter for the CFM-56 engine. Both measured ICAO data and emission indices calculated using thermodynamic cycle data are shown.

In an attempt to treat all investigated ICAO engines equally, two different types of curve fits were used. For NOx a linear interpolation on Figure 3-1 (after correcting for installation) was used. A two point linear extrapolation was used for lower and higher fuel flows, if necessary. For HC and CO (Figures 3-2 and 3-3), a least-squares fitted line of the four ICAO (installation corrected) data points was determined. A second line was plotted through the two high power (85% and 100%) points. A new point was then generated at the intercept of these two lines.

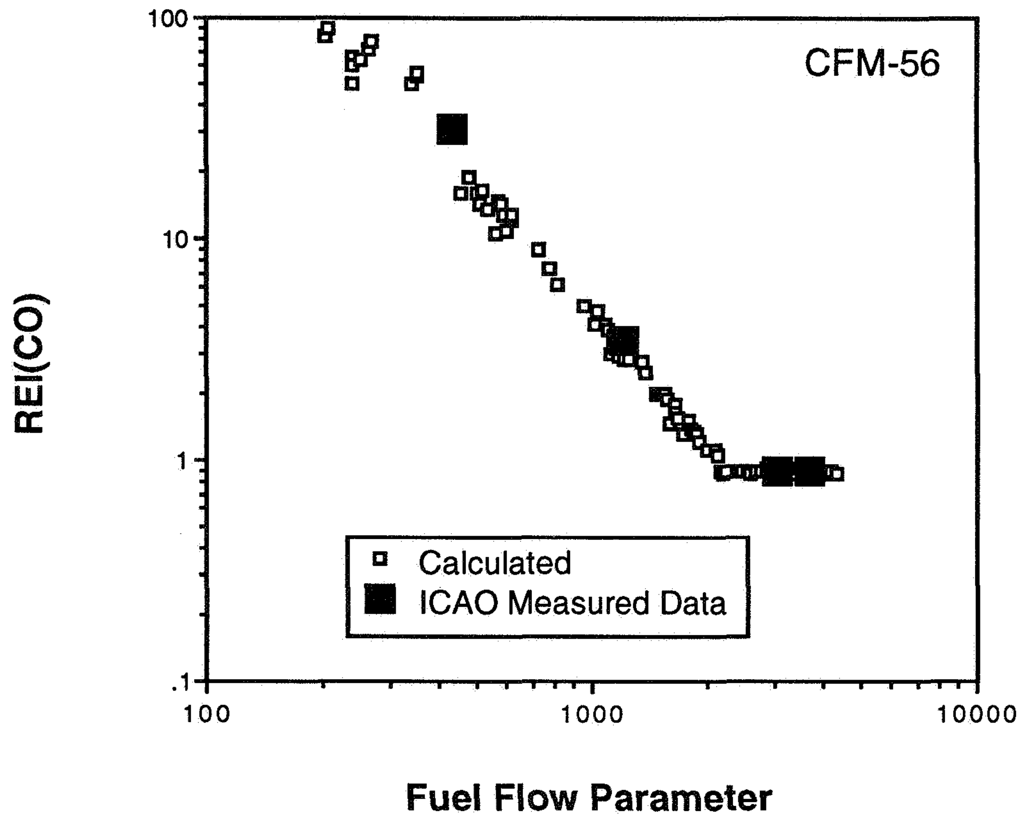


Figure 3-3. The referenced emission index (REI) for carbon monoxide as a function of fuel flow parameter for the CFM-56 engine. Both measured ICAO data and emission indices calculated using thermodynamic cycle data are shown.

A comparison of the engine manufacturer method to the Boeing fuel flow method was made using the above mentioned curve fits and airplane performance parameters from a 400 nautical mile mission. The results are in good agreement and will be described elsewhere. (Joe Zeeben, private communication)

The next step in calculating the emissions for a particular airplane mission employed the use of a Boeing proprietary airplane mission analysis program to simulate the airplane mission and determine the fuel usage of a particular aircraft for a particular mission.

3.3 HSCT Flight Profiles

In calculating the flight profiles, all aircraft were assumed to fly according to engineering design. For subsonic aircraft, cruise altitudes were calculated as a climbing cruise with the altitude determined by the weight of the aircraft. For the HSCT, supersonic flight was allowed only over water and thus the mission profiles were more complicated than for subsonic aircraft.

Actual flight profiles between city-pairs were used to distribute emissions during takeoff, subsonic and supersonic climb and cruise, and descent. Based on these mission profiles, the fuel burned and emissions were then calculated onto the database grid. Two missions which are representative of the way in which an actual HSCT would be flown are shown in Figures 3-4 and 3-5. The simplest mission (Figure 3-4) is a flight almost exclusively over water, such as Seattle to Tokyo. The HSCT would take off and climb subsonically and then supersonically to a supersonic cruise altitude. It would then fly at supersonic cruise at the optimum altitude determined by its gross weight. As it approached Tokyo, it would descend and land. The cumulative fraction of the total NO_x emissions is plotted on the right axis. The plot illustrates that about 40% of the NO_x emissions would occur during takeoff, climb, and supersonic climb.

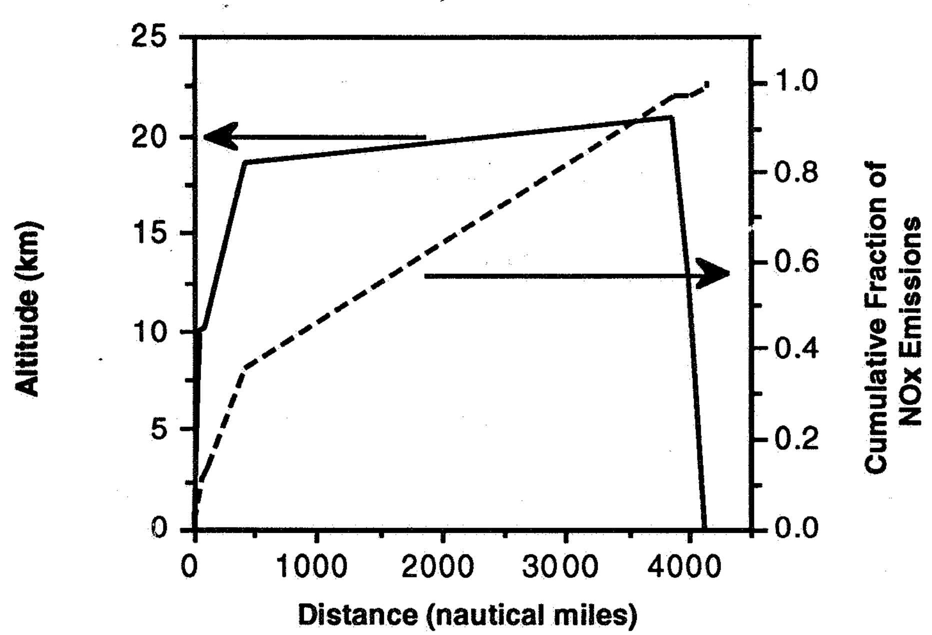


Figure 3-4. Mission profile for Mach 2.4 HSCT from Seattle to Tokyo.

A more complicated but still common mission is a flight in which one leg would be flown subsonically over land. This is illustrated in Figure 3-5 by the flight from Seattle to London. The HSCT would take off and climb to subsonic cruise altitudes. It would then cruise at subsonic speeds until reaching Hudson Bay where it would begin to climb supersonically. It would then cruise at supersonic speeds (altitude determined by the optimum performance) until descending near London. A substantial amount of the NO_x emissions would occur during the subsonic climb, subsonic cruise, and supersonic climb.

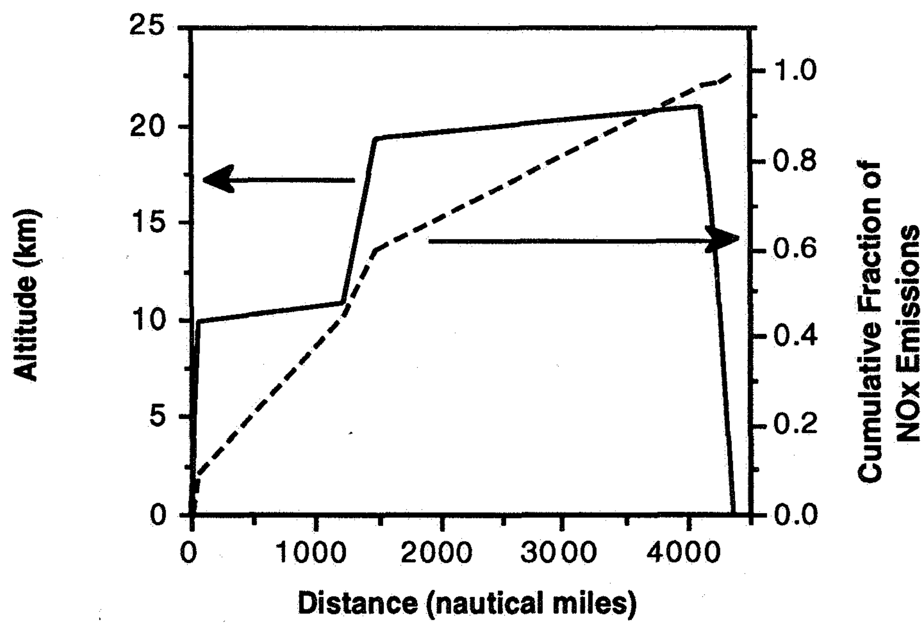


Figure 3-5. Mission profile for Mach 2.4 HSCT from Seattle to London.

A still more complicated mission, which was included in the calculations but not shown graphically, is a flight in which the aircraft might descend and climb several times to avoid flying supersonically over land. An example would be the Frankfurt to Bangkok route mentioned earlier (Figure 2-3). In this case, the HSCT would fly subsonically over Europe, supersonically over the Mediterranean, subsonically over Arabia (stopping in Bahrain) supersonically over the Indian Ocean, and then subsonically inland over the Malay peninsula. Because of the extra fuel required for supersonic climbs, such flight profiles were kept to a minimum in the scenario development.

3.4 Emissions Calculation Procedures

Boeing maintains an engineering database of aircraft performance and emissions characteristics for a number of subsonic passenger and cargo jets. For the work described here, 57 subsonic aircraft/engine configurations were used to calculate the emissions of the 1990 scenarios. Less detailed data were used for calculations of the Concorde aircraft and for turboprop aircraft. Using this database, technology modifications and improvements were projected to 2015 for subsonic jet aircraft. Calculations for the Mach 2.4 HSCT were based on the current Boeing baseline aircraft. The calculations will be described later in more detail for each component scenario. The general methodology is described below.

All aircraft were assumed to fly at designed performance. Altitudes and mission profiles were calculated based on the performance of the aircraft and its mission weight. Air traffic control constraints and routings were not considered. Flight schedules of departures for each aircraft type were based on Official Airline Guide (OAG) flight schedules for May 1990 and on projected schedules for 2015. For each aircraft type considered, a separate three-dimensional data set of fuel burned and emissions was calculated. Subsonic aircraft were flown along great circle routes between cities. For the HSCT, routing between waypoints to avoid supersonic flight over land was used for many city-pairs. The HSCT was flown along great circle routes between these waypoints. For all flights, zero prevailing winds were assumed.

To calculate the global inventory of aircraft emissions, a computer model was developed which basically combines scheduling data (departures, aircraft type) with aircraft performance and emissions data. The Global Atmospheric Emissions Code (GAEC) computer model was used to calculate fuel burned and emissions from files of airplane performance and engine emissions data. The aircraft performance file contains detailed performance input data for a wide range of operating conditions. Each engine emission input file contains emission indices tabulated as a function of fuel flow rate. The GAEC model is described in more detail in Appendix G.

For each route flown by the airplane/engine type, the takeoff gross weight required was calculated as a function of the city-pair route distance. The fuel burned was calculated for the following flight segments:

- Taxi-out
- Takeoff
- Climbout
- Subsonic Climb
- Subsonic Cruise
- Supersonic Climbout
- Supersonic Cruise
- Supersonic Descent
- Descent
- Approach and Land
- Taxi-in

For subsonic aircraft, emissions of nitrogen oxides (NOx), hydrocarbons (HC) and carbon monoxide (CO) were calculated based on the measured ground level emission indices reported to the International Civil Aviation Organization (ICAO) for current aircraft. These measurements are reported at four thrust settings. For detailed calculations of a single mission, the normal process is to use the engine emission data, the engine performance data as provided by engine thermodynamic cycle models, and the airplane performance data. Thermodynamic cycle analyses are too computationally intensive for the calculation of a global inventory of emissions. The Boeing developed simplified approach described earlier was used instead.

For the calculation of a global inventory of emissions, the measured ICAO emissions data were interpolated as a function of fuel flow rate and, corrected for temperature and pressure at altitude (based on U.S. Standard Atmosphere 1976). For the HSCT, where no hardware and thus no measurements exist, projected engine emissions data were provided by General Electric (GE) and Pratt & Whitney (P&W).

Distributions of fuel usage and emissions were done for 1° latitude $\times$ 1° longitude $\times$ 1 km altitude cells. The altitude corresponds to the geopotential altitudes of the U.S. Standard Atmosphere temperature and pressure profile and is thus pressure-gridded data. For each city-pair, the total route distance was calculated. The fuel burn rate and airplane gross weight were then calculated at discrete distances along the route path which corresponded to points where the airplane entered or left a cell (crossed any of the cells boundaries) or points where a transition in flight conditions occurred (climbout/climb, climb/cruise, cruise/descent, descent/approach and land, taxi-out/climbout, approach and land/taxi-in). The fuel burn rate would change dramatically at these transition points.

The emissions were calculated for each flight segment between the above described discrete points using the fuel burn rate within the segment. The total fuel burned in the segment was calculated as the difference in airplane gross weight at the segment end-points. The emissions were then assigned to a cell based on the coordinates of the endpoints.

3.5 Engineering Checks

The GAEC code was written to be a shortcut for the standard, computationally intensive Boeing emissions analysis process, and, as such, simplifying assumptions were made. In order to validate the GAEC code, a set of test cases were run using both GAEC and the standard Boeing Mission Analysis Program (BMAP-EMIT) process. Four routes for one aircraft/engine configuration were analyzed by both methods using the operating conditions assumed for the global emissions calculations (no winds, Standard Atmospheric conditions, 70% full passenger payload, 200 lb per passenger, etc.). Table 3-1 shows the total fuel burned and emissions generated for each portion of the flight segment as calculated by both codes.

In all of the test cases, the difference between total fuel or total emissions was less than 2% when the GAEC solution was compared to the BMAP-EMIT solution. (The differences are the percentages relative to the BMAP-EMIT solutions). The most obvious discrepancy in the data is seen in the GAEC approach data where the HC and CO emissions were overestimated by 25% and NO_x was overestimated by 13%. This is most likely due to the approach performance averaging approach-land segment, which results in higher overall emissions. However, only a small fraction of the fuel burned or emissions occur during approach. For calculations of global emissions where the primary interest is in accounting for the cruise emissions, the agreement was considered to be quite good, particularly for longer range missions.

Table 3-1. Comparison of the Global Atmospheric Emission Code (GAEC) Results with Detailed Engineering Model Calculations (BMAP/EMIT) For Four Aircraft Missions Using One Subsonic Aircraft/Engine Type

	BMAP-EMIT				GAEC				differences			
ROUTE	fuel (lb)	CO (lb)	HC (lb)	NOx (lb)	fuel (lb)	CO (lb)	HC (lb)	NOx (lb)	fuel %	CO %	HC %	NOx %
TPA-PBI	151	nmi										
taxi-out	432	18.1	1.5	1.5	432	18.2	1.5	1.6	0.0	-0.4	0.0	-8.0
takeoff	768	0.4	0.0	17.9	766	0.3	0.0	17.9	0.3	22.1	-2.5	0.2
climb	1912	0.9	0.1	45.0	1815	0.9	0.1	42.4	5.1	-7.2	-3.6	5.8
cruise	1916	4.9	0.4	22.7	2093	5.1	0.4	24.1	-9.3	-4.7	-9.2	-6.0
descent	388	30.2	2.5	1.3	397	30.5	2.5	1.3	-2.4	-0.8	-0.8	5.3
approach	400	7.1	0.6	2.7	400	5.3	0.4	2.3	0.0	25.6	24.9	13.2
taxi-in	239	10.1	0.8	0.9	240	10.1	0.8	0.9	-0.4	0.5	0.7	-2.3
total	6115	71.7	6.0	92.2	6142	70.4	5.9	90.4	-0.5	1.8	1.9	2.0
LAX-DFW	1071	nmi										
taxi-out	432	18.1	1.5	1.5	432	18.1	1.5	1.6	0.0	0.0	0.0	-6.7
takeoff	823	0.4	0.0	19.0	821	0.4	0.1	19.3	0.2	15.9	-2.3	-1.6
climb	5138	3.3	0.4	105.4	4967	3.2	0.4	100.9	3.3	3.3	2.5	4.3
cruise	16060	41.2	3.5	177.3	16148	42.1	3.6	177.9	-0.6	-2.2	-1.7	-0.3
descent	691	63.9	5.3	2.0	720	66.0	5.5	2.2	-4.1	-3.3	-3.0	-9.1
approach	400	7.1	0.6	2.7	400	5.3	0.4	2.3	0.0	26.1	24.6	12.8
taxi-in	239	10.0	0.8	0.9	240	10.0	0.8	0.9	-0.4	-0.4	1.2	-3.4
total	23704	144.2	12.2	308.9	23728	145.1	12.3	305.1	-0.1	-0.6	-0.8	1.3
JFK-OSL	3198	nmi										
taxi-out	432	18.1	1.5	1.5	432	18.2	1.5	1.6	0.0	-0.6	0.0	-6.7
takeoff	976	0.4	0.0	22.9	975	0.4	0.1	23.1	0.1	0.0	-20.5	-0.9
climb	5645	3.3	0.4	120.4	5682	3.5	0.4	118.9	-0.7	-5.7	-5.0	1.3
cruise	60965	129.4	11.6	717.6	60654	129.6	11.6	706.7	0.5	-0.2	0.0	1.5
descent	688	63.9	5.3	2.0	715	65.4	5.5	2.2	-4.0	-2.4	-2.6	-8.6
approach	400	7.1	0.6	2.7	400	5.2	0.4	2.3	0.0	26.8	24.6	12.5
taxi-in	239	9.9	0.8	0.9	240	10.0	0.8	0.9	-0.4	-0.8	-1.2	-3.4
total	69346	232.0	20.3	868.2	69099	232.4	20.3	855.7	0.4	-0.2	0.0	1.4
SIN-VIE	5242	nmi										
taxi-out	432	18.1	1.5	1.5	432	18.1	1.5	1.6	0.0	0.0	0.0	-8.0
takeoff	1087	0.4	0.1	25.8	1087	0.5	0.1	26.0	0.0	-11.4	10.6	-0.8
climb	6289	3.5	0.4	138.0	6596	3.9	0.5	141.4	-4.9	-10.8	-9.1	-2.5
cruise	111151	198.0	18.5	1386.5	110445	198.2	18.6	1365.3	0.6	-0.1	-0.1	1.5
descent	693	64.2	5.4	2.0	718	65.7	5.5	2.2	-3.6	-2.3	-2.1	-10.0
approach	400	7.1	0.6	2.7	400	5.3	0.4	2.3	0.0	25.5	24.6	12.8
taxi-in	239	9.9	0.8	0.9	240	10.0	0.8	0.9	-0.4	-1.0	-1.2	-2.3
total	120290	301.4	27.3	1538.5	119918	301.8	27.3	1539.7	0.3	-0.1	0.0	-0.1

3.6 Scenario Checks

A three-dimensional evaluation for the scheduled flights of every aircraft/engine configuration of passenger jets and turboprops included in the dataset was calculated. These were then summed to produce the various scenarios. Each three-dimensional aircraft database was checked out using the following procedure:

1. Fuel burned for the scenario was totaled over latitude, longitude, and altitude and then compared with reported global jet fuel consumption.
2. Global average emission indices were calculated for NO_X, CO, and hydrocarbons and compared with emission indices reported to ICAO to ensure the gridded emissions were reasonable.
3. The emissions were totaled over latitude and longitude, and then emission indices as a function of altitude were calculated. This is a test of the emission technology and the level of detail that went into the emission scenario calculation. Emission indices vary with power settings and thus vary at different stages of the flight. In general, NO_X emission indices should be greater during climbout than at cruise because a higher power setting is needed. Carbon monoxide and hydrocarbon emission indices will be largest at the lowest level because of low power settings during taxi operations (however, this is sensitive to the amount of time assumed during airport operations relative to takeoff).
4. The geographical distribution was checked using visual aids to make sure that it made sense for the scenario involved (Soviet Union traffic in the Soviet Union, HSCT high altitude flights only over water, etc.). Fuel burn and emissions as a function of latitude and longitude (superimposed on a map of the world) at each altitude level or summed into altitude bands were checked to ensure that routes were consistent with the type of aircraft shown and that airport locations were appropriate for each group of airplanes used in the scenario.

3.7 Water Vapor Emissions

Water vapor emissions from jet aircraft are proportional to the fuel used by the aircraft and to the hydrogen content of the fuel. Based on Boeing analyses (Reference 11) of jet fuel, the average hydrogen content is 13.84%. Thus the emission index for water vapor is given by the following expression:

$$EI(H_2O) = (8936.7) \times (\text{hydrogen fraction in fuel}) - 1.975 \times EI(HC)$$

if measured at the exit plane of the engine. Making the reasonable assumption that hydrocarbons emitted by an HSCT will be oxidized to water vapor and carbon dioxide, the effective $EI(H_2O)$ is 1237.

(Note that the emission index for hydrocarbons is given as grams of CH_4 per kg of fuel.)

3.8 Carbon Dioxide Emissions

Carbon dioxide emissions from jet aircraft are proportional to the fuel use and to the carbon content of the fuel. Based on Boeing analyses (Reference 11) of jet fuel, the average hydrogen content is 13.84%. Thus the emission index for CO_2 is given by the following expression:

$$EI(CO_2) = (3664) \times (\text{carbon fraction in fuel}) - 1.571 \times EI(CO) - 2.744 \times EI(HC)$$

if measured at the exit plane of the engine. Again, making the reasonable assumption that carbon monoxide and hydrocarbons will ultimately be oxidized to carbon dioxide, the effective $EI(CO_2)$ is 3155.

3.9 Sulfur Dioxide Emissions

Sulfur dioxide (SO_2) emissions from aircraft are proportional to the fuel use since the sulfur emissions are due to sulfur impurities in the jet fuel. The scaling factors depend on the chemical composition and are expected to vary somewhat between geographical regions due to refinery differences and different regulatory requirements. Similarly, future emissions will depend on projected changes in fuel composition.

Analyses of jet fuel samples from airports around the world yield an average sulfur content of jet A of 0.042% by weight. (Reference 11) Sulfur content in the year 2015 is projected to be 0.02%. (Reference 12)

Assuming that all fuel sulfur is oxidized to sulfur dioxide, the emission index for sulfur dioxide is given by

$$EI(SO_2) = (1998) \times (\text{sulfur fraction in fuel})$$

Based on the previous Boeing fuels analysis work (References 11-12), we recommend the emission indices (grams of emission/kilogram fuel) shown in Table 3-2 be used:

Table 3-2. Recommended emission indices in units of grams emission/kilogram fuel for 1990 and 2015.

Emission Index (EI)	1990	2015
Carbon Dioxide (CO_2)	3155	3155
Water (H_2O)	1237	1237
Sulfur dioxide (SO_2)	0.8	0.4

Since the sulfur emissions arise from impurities in jet fuel, an initial estimate can be obtained by multiplying the fuel burn reported in the NASA HSRSS scenarios (1 degree latitude x 1 degree longitude x 1 km altitude) times the average sulfur content of jet fuel for 1990 and projected to 2015. For future work, if sulfur emissions appear to be significant, this could then be refined by analyzing fuel sulfur content in different regions.

4. HSCT Emissions Scenarios

HSCT scenarios for both Mach 2.0 and Mach 2.4 HSCTs were developed assuming fleets of 500 active HSCTs, with cruise NOx emission indices of approximately 5 and 15. The scheduling and routing of the HSCT network were described in Section 2.

4.1 HSCT Description

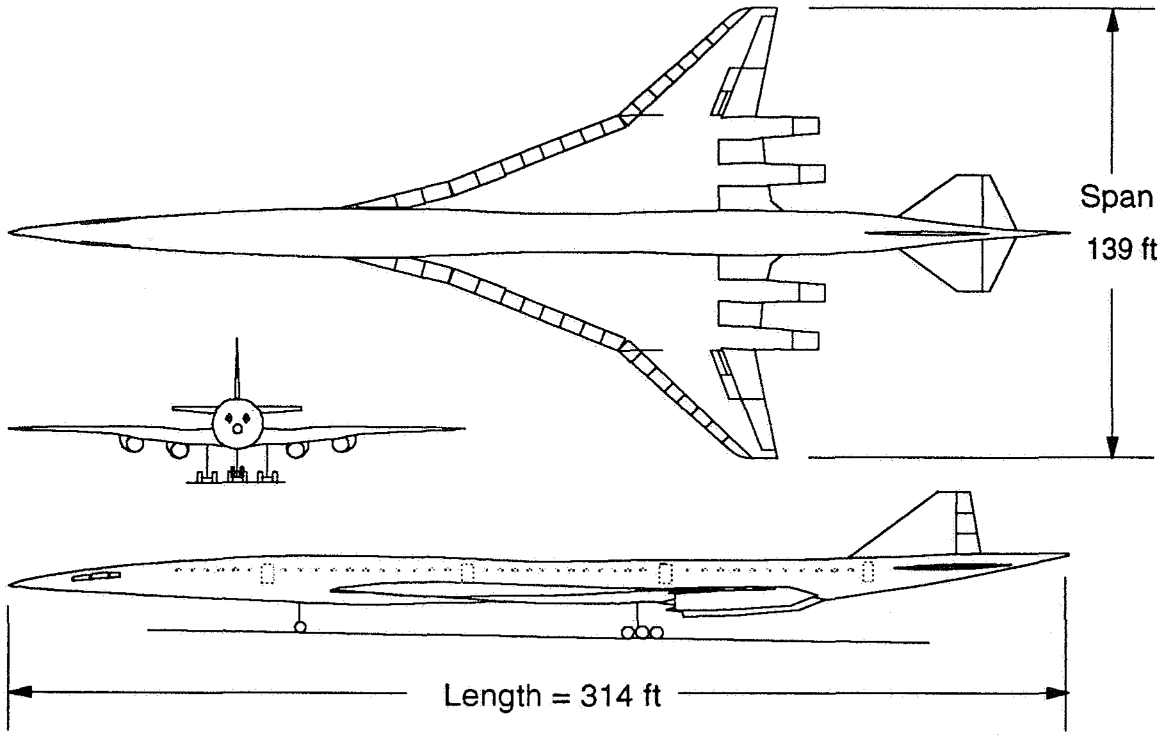
The Mach 2.4 HSCT scenarios were calculated using the Boeing preliminary design model 1080-924 with four Pratt & Whitney STJ989 turbine bypass engines with mixed compression translating center body (MCTCB2) inlets and two-dimensional semi-stowable (SS2D) nozzles. The aircraft has a cranked-arrow wing planform (see Figure 4-1) and a mostly composite structure. Overall body length is approximately 314 feet with a wing span of 139 feet. It was designed to carry 309 passengers for a range of 5000 nautical miles.

The Mach 2.0 HSCT scenarios were developed based on the preliminary design model 1080-938 with four P&W STJ1016 turbine bypass engines with MCTCB2 inlets and SS2D nozzles. The characteristics of these aircraft are summarized in Table 4-1.

Table 4-1. Summary of HSCT aircraft characteristics used in the development of the Mach 2.0 and Mach 2.4 HSCT emission scenarios.

	Mach 2.4	Mach 2.0
Model Number	1080-924	1080-938
Engine	PW STJ989	PW STJ1016
Range (nautical miles)	5000	5000
Passengers	309	309
Design Payload (lbs)	64,890	64,890
Max. Takeoff Weight (lbs)	784,608	802,872
Wing Span (ft)	139	140
Wing Area (sq. ft.)	8180	8260

Model 1080-924



Configuration Description:

Maximum takeoff weight	784,600 pounds
Wing Area	8,180 square feet
Engine	STJ989
Payload	309 passengers, tri-class
Range	5,000 nmi - supersonic cruise

Figure 4-1. HSCT Planform

Emissions data for NOx, CO, and hydrocarbons were provided by GE/P&W for a generic HSCT combustor with a nominal NO_x emission index at supersonic cruise of approximately 5 gm NO_x (as NO_2)/kg fuel. Nitrogen oxides, carbon monoxide, and hydrocarbon emission levels were calculated from these data as a function of power setting and altitude. A similar calculation was done to scale up to a nominal cruise EI (NO_x)=15 scenario. For this scaling, the combustor was assumed to operate as a conventional combustor at low power settings and as an advanced low-NO_x combustor at higher settings. Based on discussions with both engine companies, the EI(NO_x) for this case was unchanged at low power settings and increased by a factor of 3 at higher thrust settings.

4.2 HSCT Mission Profiles

The basic HSCT mission profile was assumed as follows: 10 minute taxi out, all engine takeoff ground-roll and liftoff, climbout to 1500 feet and accelerate, climb to optimum cruise altitude (subsonic or supersonic, depending on whether over land or water), climbing supersonic cruise at constant Mach, descent to 1500 feet, approach and land, and 5 minute taxi in. The HSCT was assumed to fly according to design performance, with the cruise altitude determined by the weight of the aircraft.

For a given HSCT model, fuel burned and emissions data were calculated for parametric mission cases: various takeoff weights (in increments of 50,000 pounds), two passenger-loading factors (100% and 65%), and with two cruise speeds (Mach 2.4 and Mach 0.9). These subsonic and supersonic mission profiles of varying range were used with a regression analysis to develop generalized performance for each HSCT mission segment as a function of weight. The details of this analysis are described in Appendix D.

HSCT flight profiles of fuel burn and emissions were calculated from these performance and emissions data for each HSCT mission. The departure network was described earlier in this report. These profiles with projected HSCT flight frequencies were then used to calculate the three-dimensional database, as described earlier in Section 3.

4.3 Mach 2.0 and Mach 2.4 HSCT Results

Fleet sizes and fleet fuel utilization for the Mach 2.4 and Mach 2.0 HSCT fleets are given in Table 4-2. In order to carry the same passenger demand, more Mach 2.0 HSCTs were required. This resulted in a slightly higher (2.8%) fuel use by the Mach 2.0 fleet relative to that of the Mach 2.4.

Table 4-2. Comparison of Mach 2.0 and Mach 2.4 fleet fuel use

	Mach 2.0	Mach 2.4
Fleet size	532	500
Total weekly departures	15,344	15,344
Total miles/day	7,458,802	7,458,802
Total HSCT fleet fuel (million lbs/day)	475	462

These results correspond to a daily HSCT passenger demand of 386,800 passengers. Since this HSCT network was based on passenger demand and assumed equal market penetration for both Mach 2.0 and Mach 2.4 HSCT fleets, the route statistics are the same for both Mach 2.0 and Mach 2.4 fleets. Total daily departures were 2192 with an average route distance of 3408 nautical miles.

The distances flown, fuel utilization, and NOx emission indices for different flight segments are summarized below in Tables 4-3 to 4-6 for the four cases studied.

Table 4-3. Daily mileage, fuel consumption, NOx emissions, and NOx emission index for the Mach 2.0 HSCT, EI=5 flight segments.

Flight Segment	Daily Mileage	Daily Fuel (1000 lbs)	Daily NOx (1000 lbs)	EI(NOx)
Taxi out		5,800	41	7.00
Initial Climb	84,336	34,202	277	8.10
Supersonic Climb	420,656	57,143	463	8.10
Supersonic Cruise	5,703,712	324,970	1,704	5.24
Supersonic Descent	194,285	1,356	9	6.99
Supersonic Cruise & Descent	11,892	1,102	9	8.10
Subsonic Cruise	721,699	36,411	239	6.57
Final Descent	322,224	11,916	83	6.99
Taxi in		2,240	16	6.99
Total	7,458,804	475,140	2,842	

Table 4-4. Daily mileage, fuel consumption, NOx emissions, and NOx emission index for the Mach 2.0, EI=15 flight segments.

Mission Segment	Daily Mileage	Daily Fuel (1000 lbs)	Daily NOx (1000 lbs)	EI(NOx)
Taxi out		5,800	63	10.83
Initial Climb	84,336	34,202	831	24.31
Supersonic Climb	420,656	57,143	1,389	24.30
Supersonic Cruise	5,703,712	324,970	5,113	15.73
Supersonic Descent	194,285	1,356	15	10.83
Supersonic Cruise & Descent	11,892	1,102	27	24.30
Subsonic Cruise	721,699	36,411	718	19.71
Final Descent	322,224	11,916	129	10.83
Taxi in		2,240	24	10.83
Total	7,458,804	475,140	8,308	

Table 4-5. Daily mileage, fuel consumption, NOx emissions, and NOx emission index for the Mach 2.4, EI=5 flight segments.

Mission Segment	Daily Mileage	Daily Fuel (1000 lbs)	Daily NOx (1000 lbs)	EI(NOx)
Taxi out		6,429	42	6.56
Initial Climb	93,003	37,932	328	8.65
Supersonic Climb	579,337	76,152	659	8.65
Supersonic Cruise	5,470,218	282,627	1,531	5.42
Supersonic Descent	257,054	1,669	11	6.56
Supersonic Cruise & Descent	22,505	2,100	18	8.65
Subsonic Cruise	718,847	39,585	328	8.30
Final Descent	317,840	12,663	83	6.56
Taxi in		2,455	16	6.56
Total	7,458,804	461,613	3,017	

Table 4-6. Daily mileage, fuel consumption, NOx emissions, and NOx emission index for the Mach 2.4, EI=15 flight segments.

Mission Segment	Daily Mileage	Daily Fuel (1000 lbs)	Daily NOx (1000 lbs)	EI(NOx)
Taxi out		6,429	69	10.77
Initial Climb	93,003	37,932	984	25.95
Supersonic Climb	579,337	76,152	1,976	25.95
Supersonic Cruise	5,470,218	282,627	4,593	16.25
Supersonic Descent	257,054	1,669	18	10.78
Supersonic Cruise & Descent	22,505	2,100	54	25.95
Subsonic Cruise	718,847	39,585	334	8.44
Final Descent	317,840	12,663	136	10.78
Taxi in		2,455	26	10.77
Total	7,458,804	461,613	8,192	

The NO_x emissions as a function of altitude (summed over latitude and longitude) are shown in Figure 4-2 for the Mach 2.4 and M2.0, nominal $EI(NO_x)$=5 fleets. The peak NO_x emissions at Mach 2.4 occur at 19–21 km altitudes with smaller peaks at 10–13 km altitude due to subsonic cruise. The Mach 2.0 HSCT flies at a lower cruise altitude which is evident in the emissions distribution.

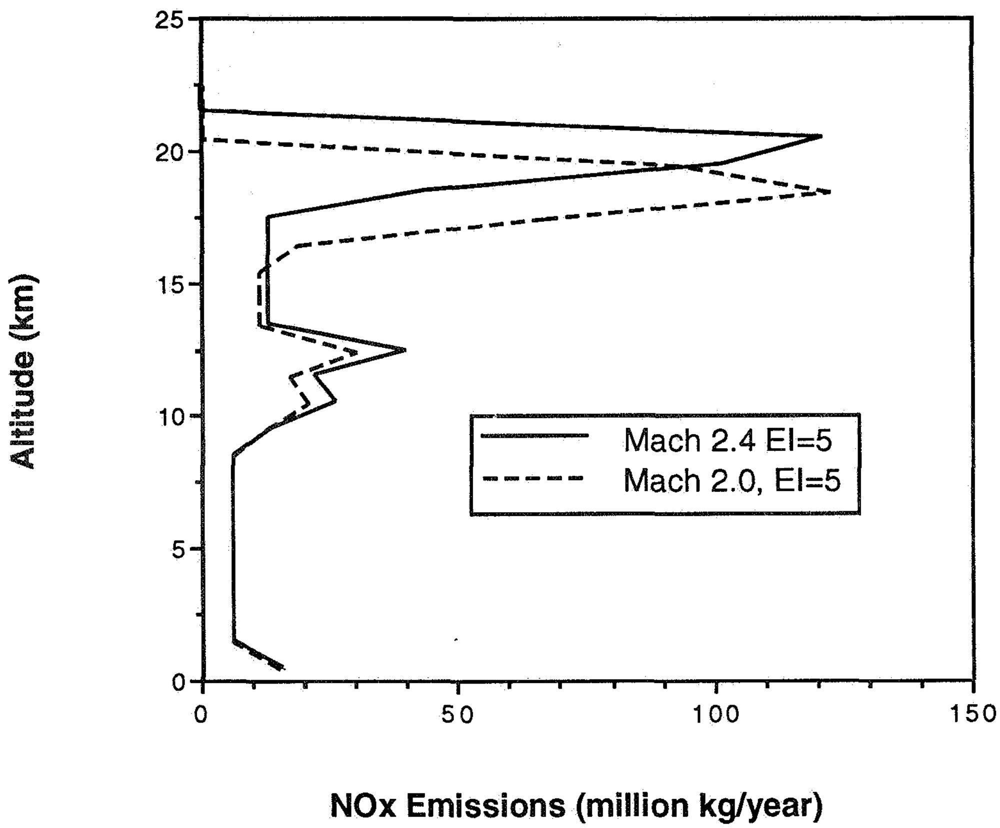


Figure 4-2. NOx emissions as a function of altitude for the Mach 2.0, EI(NOx)=5) and Mach 2.4, EI(NOx)=5 HSCT fleets. (summed over latitude and longitude).

The calculated fuel burned, emissions, and effective emission indices as a function of altitude (summed over latitude and longitude) for the Mach 2.0 and Mach 2.4 HSCTs are tabulated in Tables E1 - E4 in Appendix E.

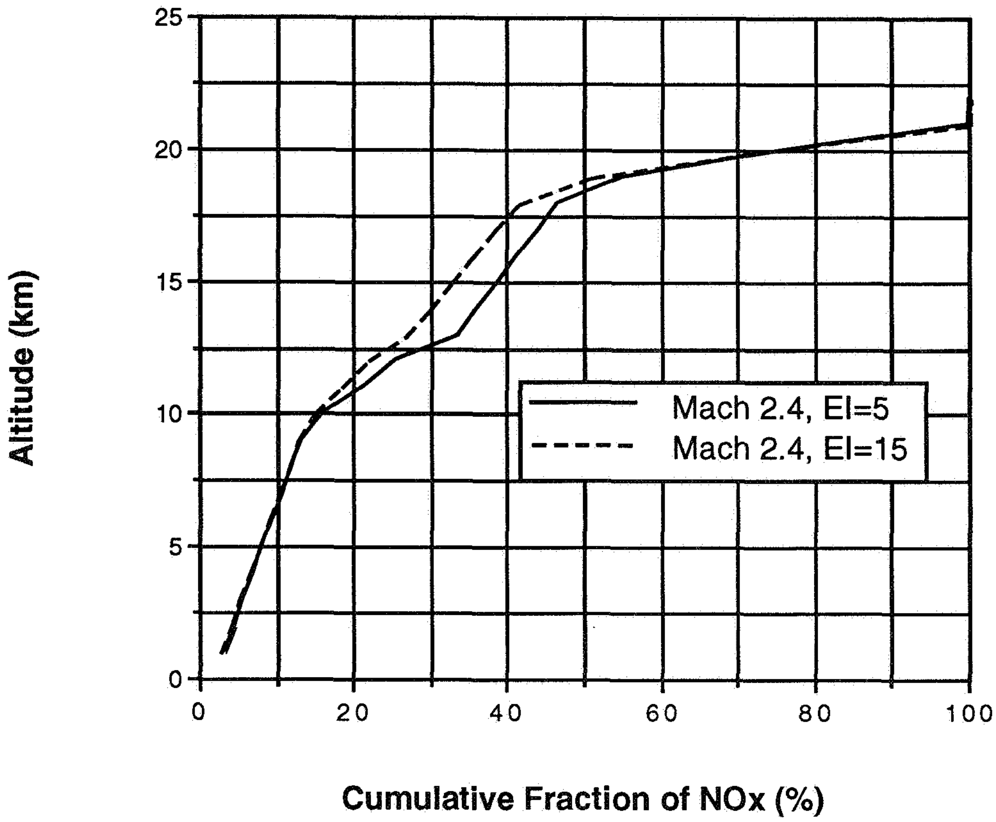


Figure 4-3. Cumulative fraction of NOx emissions as a function of altitude (summed over latitude and longitude) for the Mach 2.4 HSCT fleet.

Figure 4-3 shows the cumulative fraction of NO_x emissions plotted as a function of altitude for the Mach 2.4 HSCT fleet with nominal EI(NOx)=5 and EI(NOx)=15. Approximately 53% of the NO_x emissions from a Mach 2.4 HSCT fleet will occur above 17 km altitude, with 24 % above 20 km.

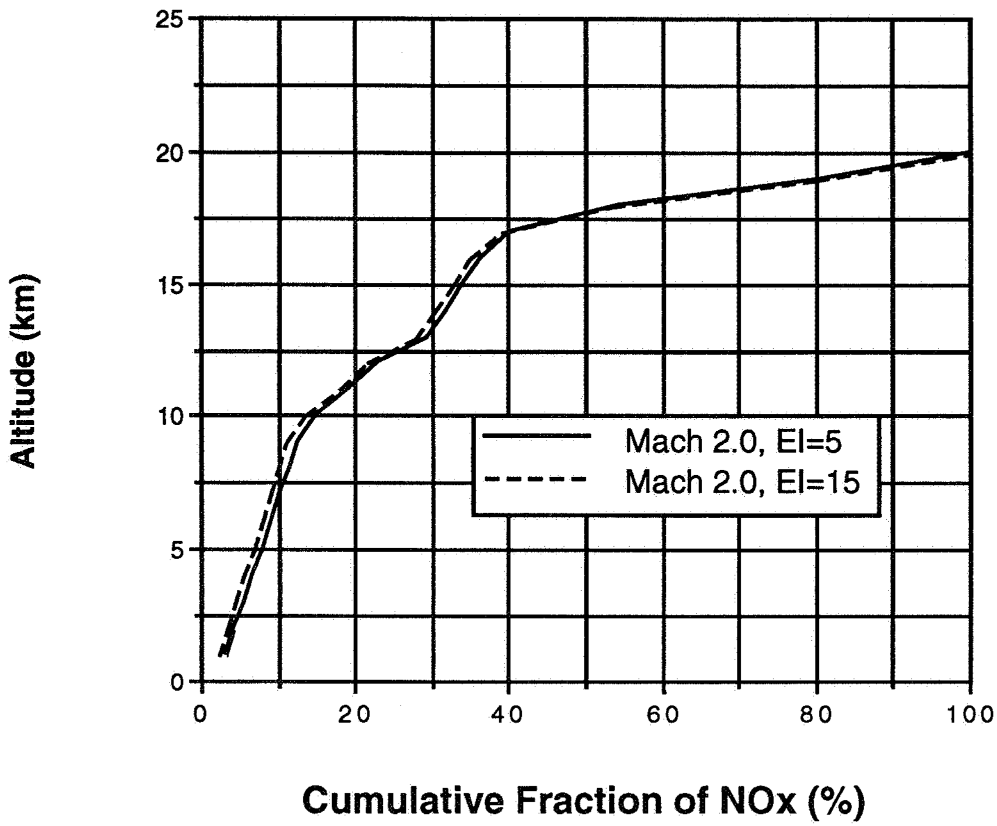


Figure 4-4. Cumulative fraction of NOx emissions as a function of altitude (summed over latitude and longitude) for the Mach 2.0 HSCT fleet.

By comparison with the Mach 2.4 HSCT , the Mach 2.0 fleet emissions occur at lower altitude, with no emissions above 20 km, as shown in Figure 4-4.

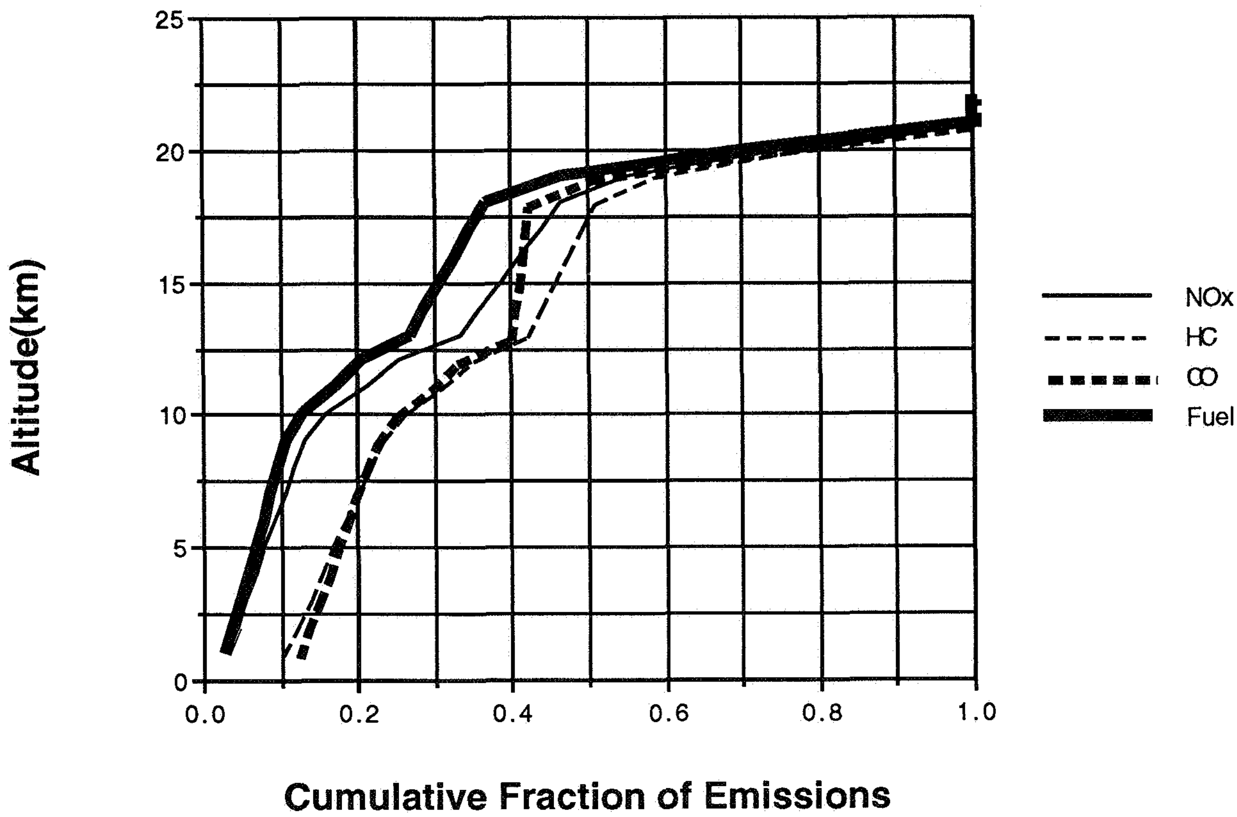


Figure 4-5. Cumulative fraction of fuel burned, NOx, CO, and hydrocarbons as a function of altitude for the Mach 2.4 EI(NOx)=5 fleet.

Figure 4-5 shows the cumulative fraction of fuel burn and emissions plotted as a function of altitude for the Mach 2.4 EI(NOx)=5 HSCT fleet. This figure illustrates that a significantly larger fraction of the CO and hydrocarbon emissions occur at lower altitude compared to the NOx emissions or the fuel burned.

The three-dimensional character of the data set is illustrated in Figure 4-6 which shows NO_X emissions for the Mach 2.4 HSCT (nominal $EI(NO_X)=5$) case. Emissions at 18–21 km due to supersonic cruise are concentrated in the northern hemisphere, particularly between 40° and 50° N latitude. Flights above 13 km occur only over water.

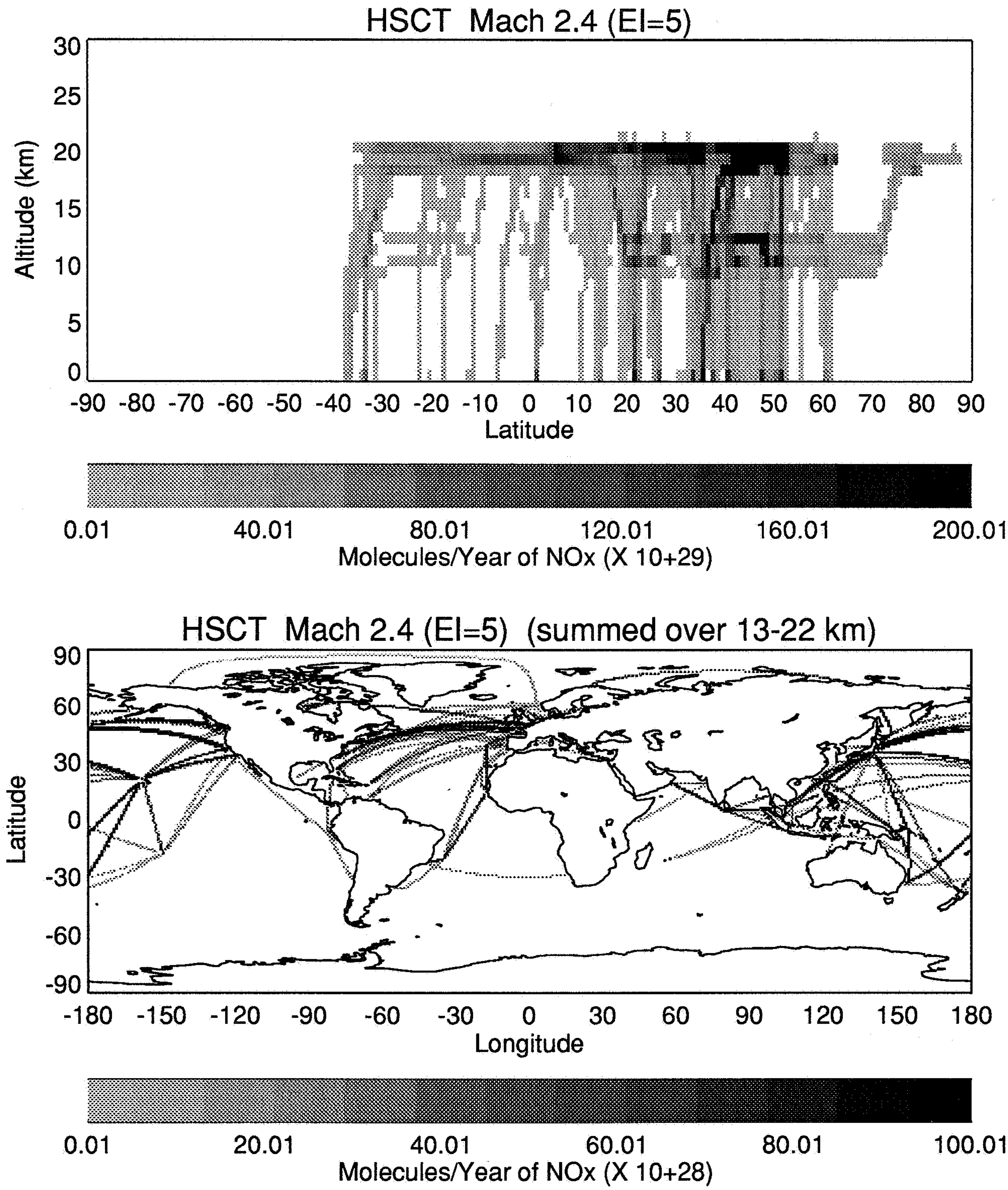


Figure 4-6. NOx emissions for a fleet of 500 Mach 2.4 HSCTs as a function of altitude and latitude (summed over longitude) (top panel) and as a function of latitude and longitude (summed over altitude) (bottom panel), considering only the HSCT emissions.

HSCT emissions are calculated to occur mostly at northern mid-latitudes . This is shown in Figures 4-7 and 4-8. Only 3% of the total fuel burned occurs north of 60° N latitude. No flights occur south of 40° S latitude. Approximately 32% of the fuel burned occurs between 30° S and 30° N latitude.

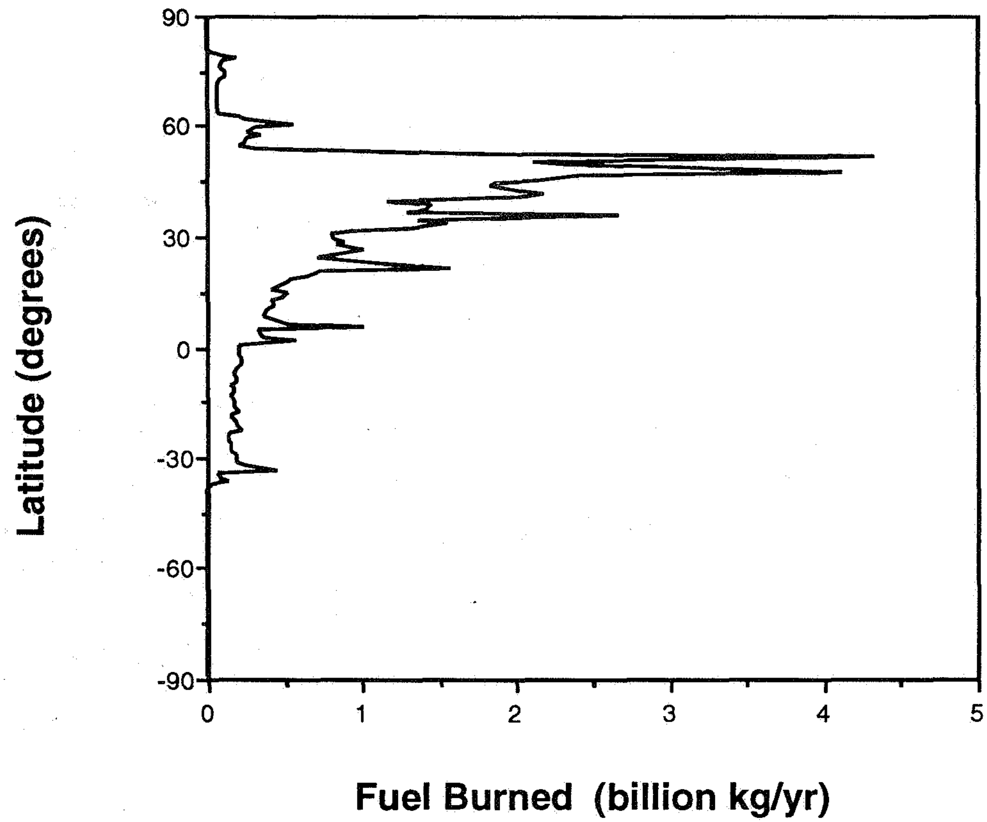


Figure 4-7. Fuel burned as a function of latitude for the Mach 2.4 HSCT fleet only (summed over altitude and longitude).

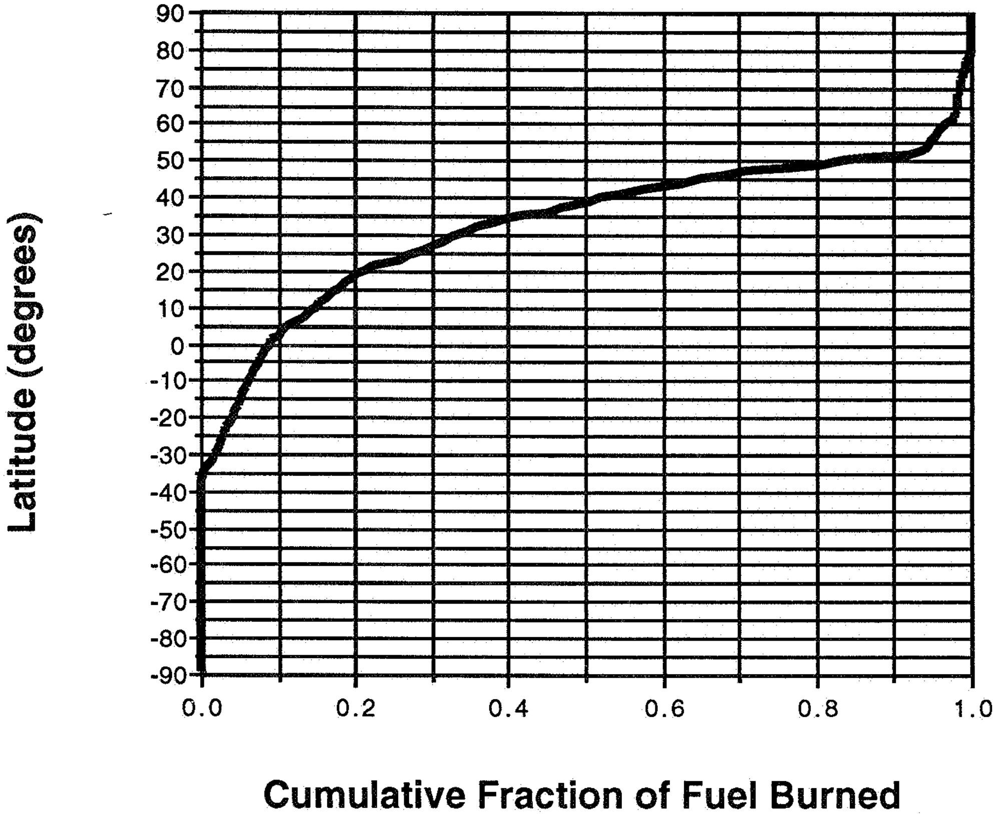


Figure 4-8. Cumulative fraction of fuel burned as a function of latitude for the Mach 2.4 HSCT fleet only (summed over altitude and longitude).

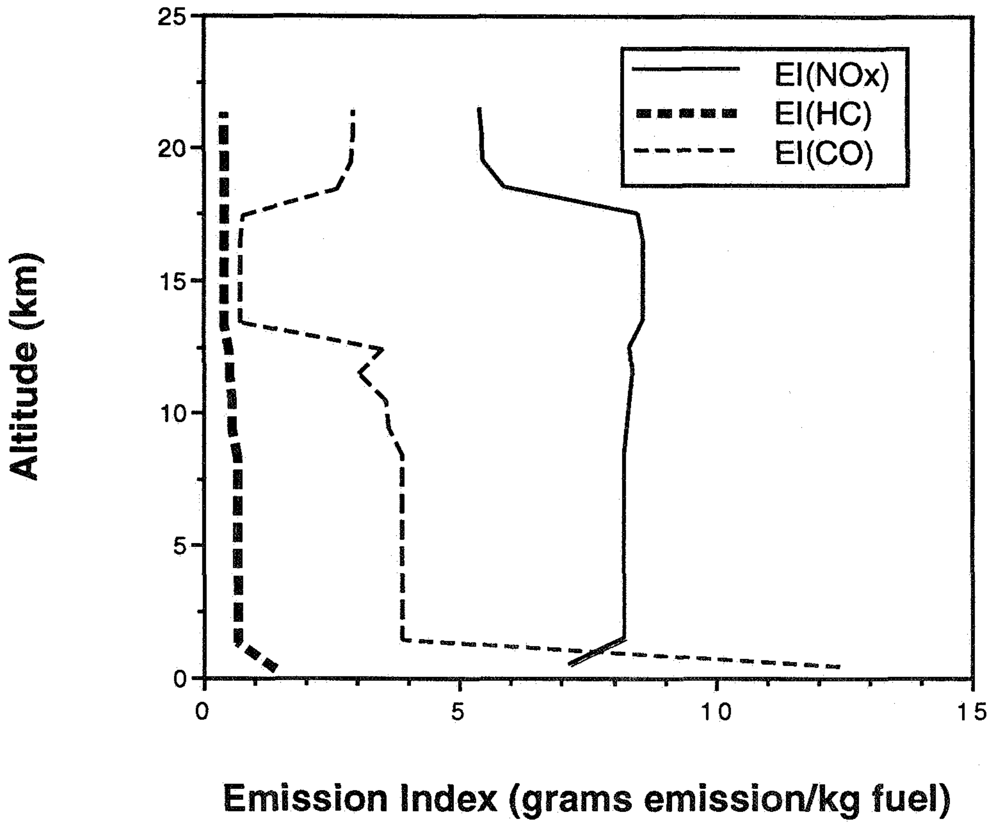


Figure 4-9. Emission indices for NOx, hydrocarbons, and carbon monoxide as a function of altitude for the Mach 2.4, EI(NOx)=5 fleet only.

Emission indices for NO_x, CO, and hydrocarbons vary as a function of altitude as shown in Figure 4-9. Nitrogen oxide levels are highest during times of high thrust requirements (i.e., climbout and supersonic climb), while CO and hydrocarbons are much lower at those times. During periods of low power, the CO and hydrocarbons are proportionally higher.

5. Year 1990 Scheduled Aircraft Emission Scenarios

Fuel burn and emissions (NO_X, CO, hydrocarbons) were calculated for scheduled 1990 turboprop, cargo, and airliner traffic. Flight frequencies and equipment types were taken from the May 1990 Official Airline Guide (OAG) and used as representative of the annual average. Aircraft performance data and emission characteristics were assembled for 57 subsonic jet aircraft/engine configurations, for the supersonic Concorde, and for three sizes of turboprop aircraft.

Airplanes known to have similar performance characteristics and to operate similarly were combined under single airplane models. Airplanes for which Boeing does not have performance data (e.g., Russian aircraft) were analyzed using performance data from airplanes estimated to have similar operating and performance characteristics. The results are described below.

5.1 1990 Scheduled Airliner and Cargo Scenario

The aircraft included in the 1990 scheduled airliner and cargo scenario calculation are shown in Table 5-1. A total of 37,069 flights per day were considered, with 22,596,338 miles flown per day. This included 14,785 city pairs between 1,639 cities.

Table 5-2 summarizes the global fuel use, emissions and globally averaged emission indices for each of the aircraft/engine combinations included in the compilation of the database. As the table illustrates, the emissions characteristics of the older aircraft (e.g., 707, DC-8) are quite different from those of more modern aircraft (e.g., 757, 767).

A three-dimensional database was calculated for each of the aircraft/engine configurations. These were then summed over all the aircraft types to produce a three-dimensional scenario of scheduled airliner and cargo aircraft. The fuel burned, emissions, and emission indices as a function of altitude for scheduled airliner and cargo aircraft are tabulated in Table E-5 in Appendix E.

Table 5-1. Departure statistics for 1990 scheduled airliner and cargo aircraft.

Aircraft/engine	Maximum Range Distance (nm)	Total Daily Distance (nm)	Total Daily Departures	Average Route Distance (nm)
707-320-C_JT3D-7	5531	122707	144	853
727-100_JT8D-9	2542	85133	174	491
727-200_JT8D-9	2612	474599	1196	397
727-200_JT8D-15	2792	2690180	4637	580
737-200_JT8D-9	2318	902360	2480	364
737-200_JT8D-15	2250	1380118	3820	361
737-300+400+500_CFM56	2444	2956560	5804	509
747-100+200_JT9D-7A	5561	709461	311	2279
747-100+200_CF6-50E2	6537	720532	315	2287
747-200_JT9D-7J	6267	105030	44	2403
747-200_JT9D-7Q	6078	593654	248	2391
747-200_JT9D-7R4G2	6609	55586	25	2215
747-200_RB211	6736	481714	190	2535
747-300_CF6-50E2	6159	34339	16	2187
747-300_CF6-80C2	6929	34764	11	3280
747-300_JT9D-7R4G2	6480	139486	55	2555
747-300_RB211	6538	63629	32	1995
747-400_CF6-80C2	7555	59611	31	1917
747-400_PW4056	7510	179918	56	3213
747-40_RB211	7494	94781	33	2889
747SP_JT9D-7	6501	138436	50	2747
747SP_RB211	6929	2408	4	617
757-200_PW2000	4161	397387	509	781
757-200_RB211	3963	299246	407	735
767-200+ER+CF6-80A	5691	389279	389	1002
767-200+ER_JT9D-7R4	5688	331352	202	1643
767-200+ER_PW4000	6633	9357	4	2600
767-200+ER_CF6-80C2	6844	78632	50	1570
767-300+ER_CF6-80C2	6351	136937	165	832
767-300+ER_JT9D-7R4	4343	31246	52	600
767-300+ER_PW4060	6157	102466	79	1292
767-300ER_RB211	6035	8310	26	320
A300-600+ER_CF6-80C2	4488	72687	78	932
A300-B2+B4_CF6-50C2	3500	695597	1070	650
A310-200+300_CF6-80A	4374	455270	454	1003
A320-200+300_CFM56-5-A	3090	157621	354	445

Table 5-1. (cont) Departure statistics for 1990 scheduled airliner and cargo aircraft.

Aircraft/engine	Maximum Range Distance (nm)	Total Daily Distance (nm)	Total Daily Departures	Average Route Distance (nm)
BAC111_SPEY-512	1513	102072	302	338
BAE146_ALF502	1243	186770	763	245
CARAVELLE-10B_JT8D	2054	16248	62	264
CONCORDE		21024	7	3066
DASSMR_JT8D-7	2275	15688	62	254
DC10-10_CF6-6D	3459	175135	143	1225
DC10-30_CF6-50E2	6064	1256978	692	1815
DC8-63_JR3D	4834	132540	107	1240
DC8-71_CFM56-B1	4776	203639	202	1007
DC9-10+20+30_JT8D	1454	1393088	4078	342
DC9-40+50_JT8D	1500	235049	636	370
FOKKER-100_TAY-650	1990	67887	229	297
FOKKER-28_SPEY-555	1500	316985	1229	258
IL-62_JT3D-7	5531	138373	66	2087
IL-86_RB211	2969	83116	73	1143
L1011_RB211	5785	675739	489	1381
MD-82_JT8D-217	2157	1647721	3256	506
MD-87_JT8D-217	2515	73086	114	641
TRIDENT_JT8D-7	2500	13577	21	635
TU134_JT8D-7	1454	117541	267	440
TU154_JT8D-15	2792	436081	505	864
YAK-40+42_JT8D-7	2500	97609	251	389

Table 5-2. Globally summed fuel burned, emissions, and emission indices for each aircraft included in the 1990 scheduled airline and cargo database.

Aircraft/engine	Fuel (kg/year)	NOx (kg/year)	HC (kg/year)	CO (kg/year)	Globally Summed Emission Indices EI (NOx)	EI (HC)	EI (CO)
707-320B-C_JT3D-7	5.33E+08	3.00E+06	1.80E+07	1.96E+07	5.64	33.70	36.85
727-100_JT8D-9	2.71E+08	2.16E+06	5.62E+05	2.00E+06	7.98	2.08	7.39
727-200_JT8D-15	1.04E+10	1.01E+08	6.81E+06	3.85E+07	9.75	0.66	3.71
727-200_JT8D-9	1.97E+09	1.93E+07	1.79E+06	8.68E+06	9.76	0.91	4.39
737-200_JT8D-15	3.79E+09	3.51E+07	3.02E+06	1.84E+07	9.25	0.80	4.86
737-200_JT8D-9	2.43E+09	2.11E+07	2.72E+06	1.28E+07	8.67	1.12	5.26
737-300+400+500_CFM56	6.69E+09	7.11E+07	2.89E+06	5.58E+07	10.63	0.43	8.34
747-100+200_CF6-50E2	5.49E+09	8.41E+07	5.56E+06	3.09E+07	15.34	1.01	5.62
747-100+200_JT9D-7A	5.43E+09	7.98E+07	9.48E+06	1.88E+07	14.70	1.75	3.47
747-200_JT9D-7J	8.14E+08	1.22E+07	1.48E+06	2.81E+06	14.98	1.82	3.46
747-200_JT9D-7Q	4.74E+09	5.49E+07	6.22E+06	1.77E+07	11.58	1.31	3.73
747-200_JT9D-7R4G2	4.08E+08	4.84E+06	1.62E+05	1.11E+06	11.86	0.40	2.73
747-200_RB211	3.52E+09	6.92E+07	1.65E+06	6.12E+06	19.62	0.47	1.74
747-300_CF6-50E2	2.65E+08	4.15E+06	2.73E+05	1.44E+06	15.67	1.03	5.44
747-300_CF6-80C2	2.49E+08	2.78E+06	2.24E+05	1.01E+06	11.16	0.90	4.04
747-300_JT9D-7R4G2	1.07E+09	1.34E+07	4.02E+05	2.68E+06	12.56	0.38	2.50
747-300_RB211	4.87E+08	1.00E+07	2.81E+05	1.03E+06	20.55	0.58	2.11
747-400_CF6-80C2	4.27E+08	4.76E+06	5.18E+05	2.25E+06	11.15	1.21	5.27
747-400_PW4056	1.30E+09	1.69E+07	2.89E+05	3.76E+06	12.99	0.22	2.88
747-400_RB211	6.91E+08	9.94E+06	1.86E+06	1.80E+06	14.38	2.69	2.61
747SP_JT9D-7	9.45E+08	1.23E+07	2.20E+06	4.29E+06	12.99	2.33	4.54
747SP_RB211	1.74E+07	3.35E+05	3.81E+04	1.31E+05	19.26	2.19	7.55
757-200_PW2000	1.09E+09	1.45E+07	5.42E+05	5.33E+06	13.36	0.50	4.89
757-200_RB211	8.65E+08	1.03E+07	1.63E+06	5.73E+06	11.89	1.89	6.62
767-200+ER_CF6-80A	1.39E+09	1.85E+07	1.58E+06	7.47E+06	13.27	1.13	5.37
767-200+ER_CF6-80C2	2.60E+08	2.60E+06	4.53E+05	1.88E+06	10.00	1.74	7.25
767-200+ER_JT9D-7R4	1.13E+09	1.47E+07	3.70E+05	2.65E+06	13.08	0.33	2.35
767-200+ER_PW4000	3.13E+07	3.70E+05	9.45E+03	1.20E+05	11.83	0.30	3.84
767-300+ER_CF6-80C2	5.29E+08	6.02E+06	1.24E+06	4.89E+06	11.38	2.35	9.24
767-300+ER_JT9D-7R4	1.32E+08	2.15E+06	5.52E+04	3.97E+05	16.25	0.42	3.00
767-300+ER_PW4060	3.82E+08	4.91E+06	1.68E+05	1.97E+06	12.86	0.44	5.15
767-300ER_RB211	4.18E+07	8.04E+05	1.15E+05	3.98E+05	19.25	2.75	9.54
A300-600+ER_CF6-80C2	3.01E+08	3.51E+06	6.03E+05	2.29E+06	11.65	2.00	7.62
A300-B2+B4_CF6-50C2	3.61E+09	6.42E+07	4.40E+06	2.36E+07	17.77	1.22	6.54
A310-200+300_CF6-80A	1.65E+09	2.21E+07	1.75E+06	8.28E+06	13.34	1.06	5.00
A320-200+300_CFM56-5-A1	3.84E+08	5.34E+06	2.50E+05	2.15E+06	13.91	0.65	5.60
BAC111_SPEY-512	2.60E+08	2.62E+06	2.36E+05	1.84E+06	10.07	0.91	7.07
BAE146_ALF502	5.49E+08	5.09E+06	4.95E+06	1.33E+07	9.27	9.02	24.18
CARAVELLE-10B_JT8D	5.06E+07	4.21E+05	5.60E+04	2.66E+05	8.31	1.11	5.26
CONCORDE	1.47E+08	2.23E+06	1.20E+06	9.07E+06	15.15	8.14	61.53

Table 5-2.(cont) Globally summed fuel burned, emissions, and emission indices for each aircraft included in the 1990 scheduled airline and cargo database.

Aircraft/engine	Fuel (kg/year)	NOx (kg/year)	HC (kg/year)	CO (kg/year)	Globally Summed Emission Indices EI (NOx)	EI (HC)	EI (CO)
DASSMR_JT8D-7	4.56E+07	3.63E+05	4.08E+05	8.88E+05	7.97	8.94	19.47
DC10-10_CF6-6D	9.73E+08	1.88E+07	6.11E+05	3.64E+06	19.36	0.63	3.74
DC10-30_CF6-50E2	6.77E+09	9.78E+07	6.22E+06	4.72E+07	14.44	0.92	6.97
DC8-63_JT3D	6.30E+08	3.82E+06	1.03E+07	1.13E+07	6.07	16.31	17.96
DC8-71_CFM56-B1	8.39E+08	8.61E+06	2.35E+05	4.04E+06	10.26	0.28	4.82
DC9-10+20+30_JT8D	3.61E+09	2.99E+07	5.46E+06	2.70E+07	8.29	1.51	7.48
DC9-40+50_JT8D	6.99E+08	6.94E+06	7.16E+05	3.99E+06	9.93	1.02	5.71
FOKKER-100_TAY-650	1.52E+08	1.19E+06	4.49E+05	4.42E+06	7.83	2.96	29.13
FOKKER-28_SPEY-555	7.70E+08	7.30E+06	5.37E+05	6.85E+06	9.48	0.70	8.90
IL-62_JT3D-7	5.65E+08	3.14E+06	9.51E+06	1.28E+07	5.55	16.82	22.62
IL-86_RB211	5.28E+08	9.54E+06	9.07E+05	3.03E+06	18.05	1.72	5.74
L1011_RB211	3.47E+09	6.22E+07	2.24E+06	9.36E+06	17.90	0.65	2.70
MD-82_JT8D-217	4.59E+09	5.55E+07	7.28E+06	2.29E+07	12.10	1.59	4.99
MD-87_JT8D-217	1.75E+08	1.91E+06	3.25E+05	9.88E+05	10.90	1.86	5.66
TRIDENT_JT8D-7	4.48E+07	3.58E+05	2.89E+05	5.83E+05	7.99	6.45	13.01
TU134_JT8D-7	2.86E+08	2.23E+06	1.40E+06	4.18E+06	7.79	4.91	14.63
TU154_JT8D-15	1.57E+09	1.48E+07	9.79E+05	5.26E+06	9.45	0.62	3.35
YAK-40+42_JT8D-7	3.61E+08	3.11E+06	2.76E+06	5.28E+06	8.60	7.63	14.60
Total	9.08E+10	1.14E+09	1.37E+08	5.17E+08	12.56	1.50	5.69

(1.00E+09 = 1.00×10^9)

The NOx emission characteristics shown here for the Concorde differ somewhat from those previously published in Reference 4. Subsequent to the preparation of that report, an error in the NOx emission indices used for Concorde was discovered and corrected. The values shown in Table 5-2 reflect the corrected numbers. Since the number of flights by the Concorde are so few (see Table 5-1), this correction has little effect on the three dimensional emission inventory. Thus, the data file available to atmospheric modelers at NASA Langley was not modified.

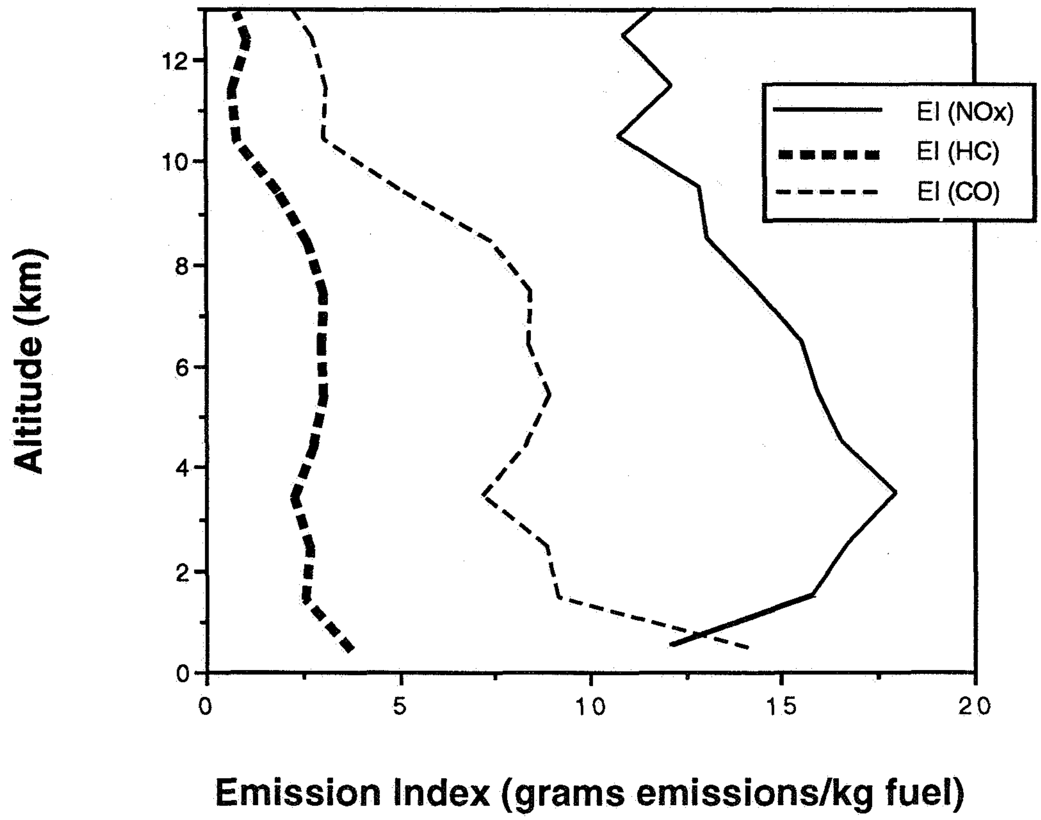


Figure 5-1. Emission indices for NOx, carbon monoxide, and hydrocarbons as a function of altitude for the 1990 scheduled airliner and cargo scenario.

The emission indices vary significantly as a function of altitude as shown in Figure 5-1. Nitrogen oxide emission indices are higher during takeoff and climb and drop during cruise. Emission indices above 13 km are due to the Concorde and contribute relatively little to the global emissions because of the small number of flights by the Concorde (7 flights/day). (See Table E-5 in Appendix E for a tabulation of global emission indices as a function of altitude)

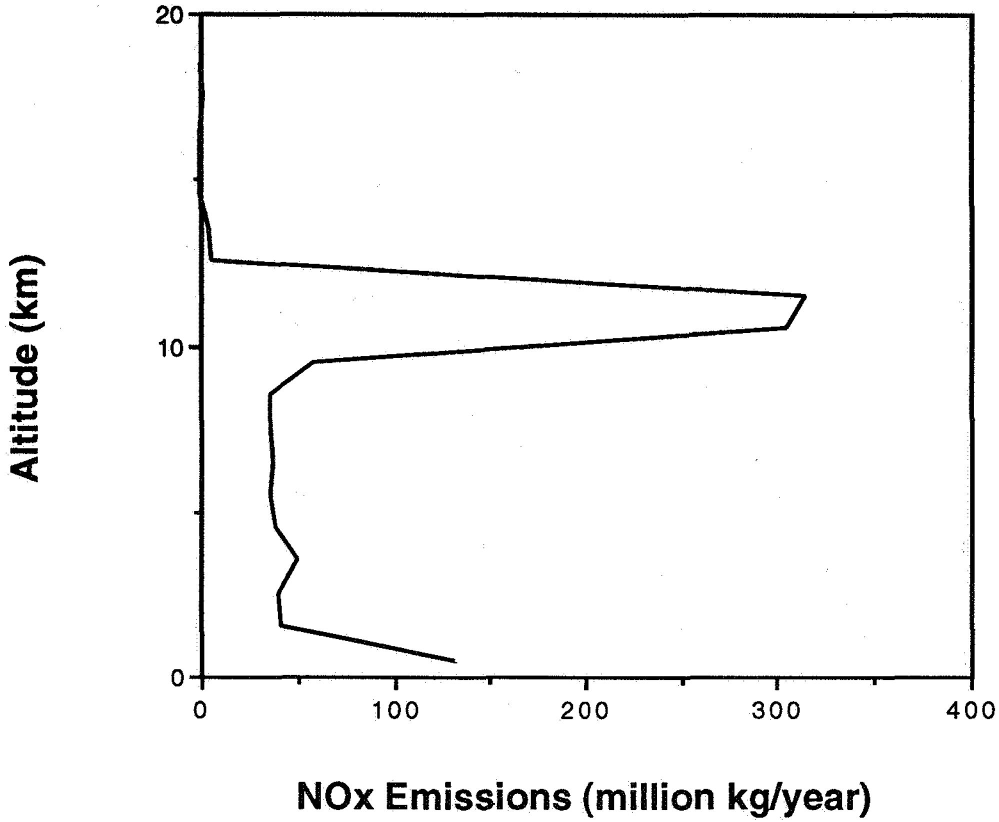


Figure 5-2. NOx emissions as a function of altitude for the 1990 scheduled airliner and cargo fleet (summed over latitude and longitude).

As shown in Figures 5-2 and 5-3, most (60–65%) of the fuel burned and NO_x emissions occur between 9 and 12 km altitude. As shown in Figure 5-3, approximately 60–70% of the CO and hydrocarbons emissions are produced on takeoff and climb out, and thus occur below 9 km.

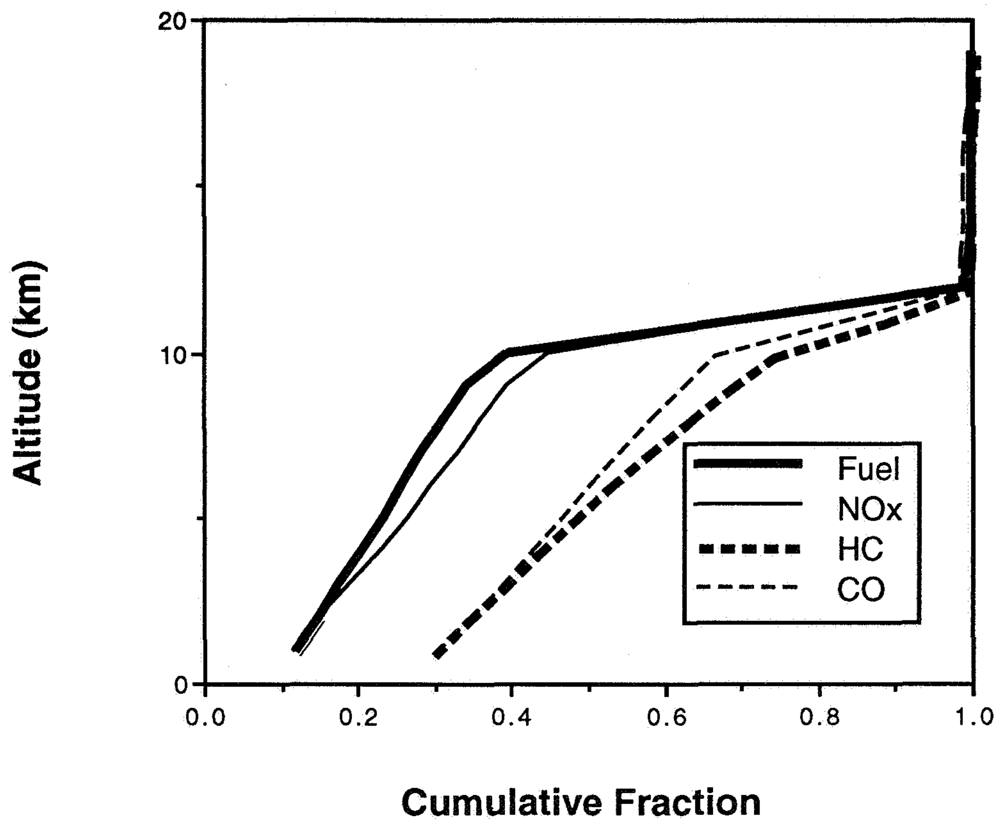


Figure 5-3. Cumulative fraction of fuel burned, NOx, hydrocarbons, and carbon monoxide as a function of altitude (summed over latitude and longitude) for the 1990 scheduled airliner and cargo fleet.

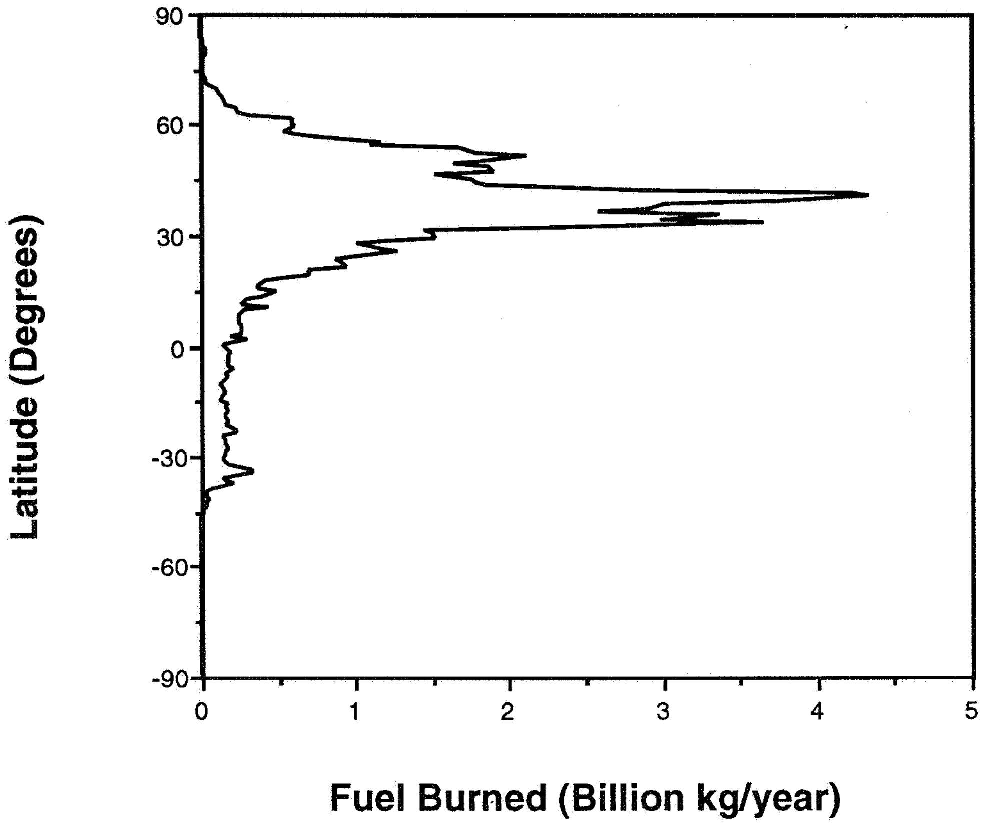


Figure 5-4. Fuel burned as a function of latitude (summed over altitude and longitude) for the 1990 scheduled airliner and cargo fleet.

Most scheduled commercial air traffic occurs in the Northern hemisphere. Figure 5-4 shows the distribution of fuel burned from scheduled jet passenger and cargo traffic as a function of latitude. As shown in Figure 5-5, approximately 70% of the fuel burn from scheduled jet passenger and cargo aircraft occurs north of 30° North latitude, with the majority between 30° and 60° North.

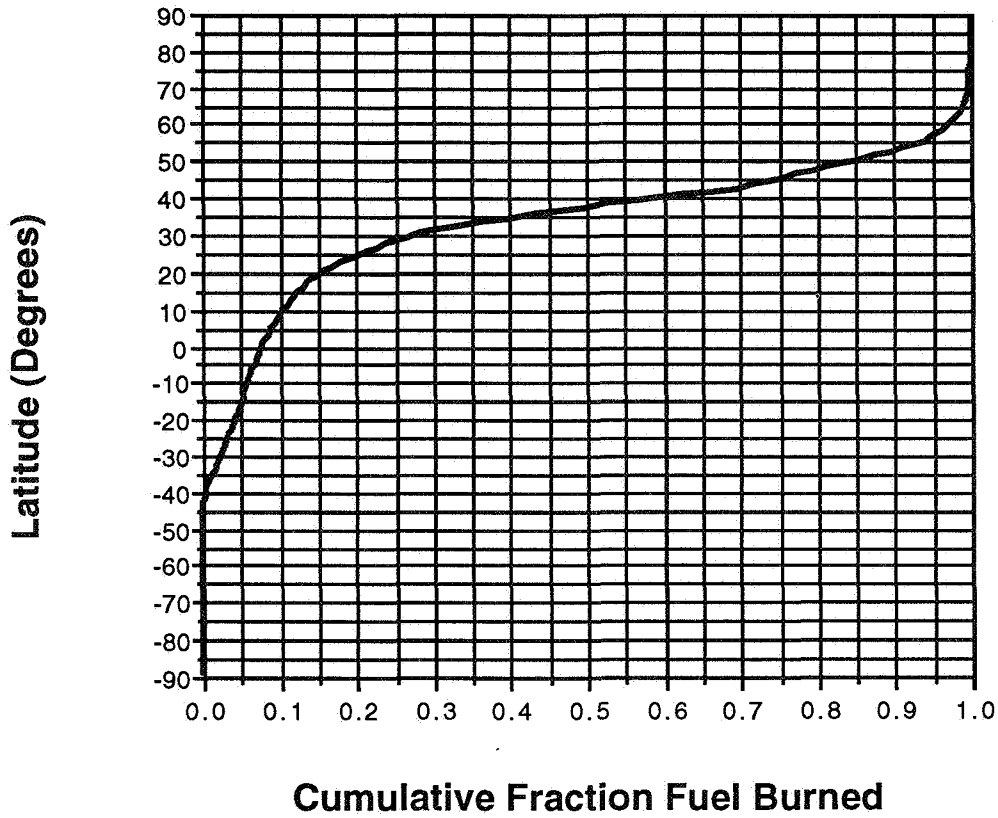


Figure 5-5. Cumulative fraction of fuel burned as a function of latitude (summed over altitude and longitude) for the 1990 scheduled airliner and cargo fleet.

5.2 1990 Scheduled Turboprop Scenario

Three twin-engine turboprops were selected to represent small, medium, and large categories of turboprops flying commercially in 1990. The three size categories corresponding to approximately 19, 36, and 50 seat aircraft. Turboprop flights for 9,356 city pairs between 2,707 cities were included in the analysis. The results are tabulated in Tables 5-3 and 5-4. Since turboprop fuel burn was found to be a small fraction (1.1%) of the reported global jet fuel consumption, it will not be discussed in detail here. The fuel burned, emissions, and emission indices are tabulated as a function of altitude in Table E-6 of Appendix E.

Table 5-3. Departure statistics for 1990 scheduled turboprops.

Aircraft	Total Daily Distance (nm)	Total Daily Departures	Average Route Distance (nm)
Small turboprops	980300	7399	132
Medium turboprops	714576	4784	149
Large Turboprops	989875	6343	156
Total	2,684,751	18,526	

Table 5-4. Globally summed fuel burned, emissions, and emission indices for the 1990 scheduled turboprops.

Size	Fuel (kg/year)	NOx (kg/year)	HC (kg/year)	CO (kg/year)	EI NOx	EI HC	EI CO
Large turboprops	7.98E+08	9.65E+06	0.00E+00	3.73E+06	12.10	0.00	4.68
Medium turboprops	5.46E+08	5.96E+06	8.67E+05	3.09E+06	10.92	1.59	5.65
Small turboprops	6.42E+08	4.91E+06	2.44E+05	2.96E+06	7.65	0.38	4.60
Total	1.99E+09	2.05E+07	1.11E+06	9.77E+06	10.34	0.56	4.92

Because turboprop aircraft fly at lower altitudes, their emissions are injected lower in the atmosphere. NOx emissions as a function of altitude for the 1990 scheduled turboprop aircraft fleet are shown in Figure 5-6.

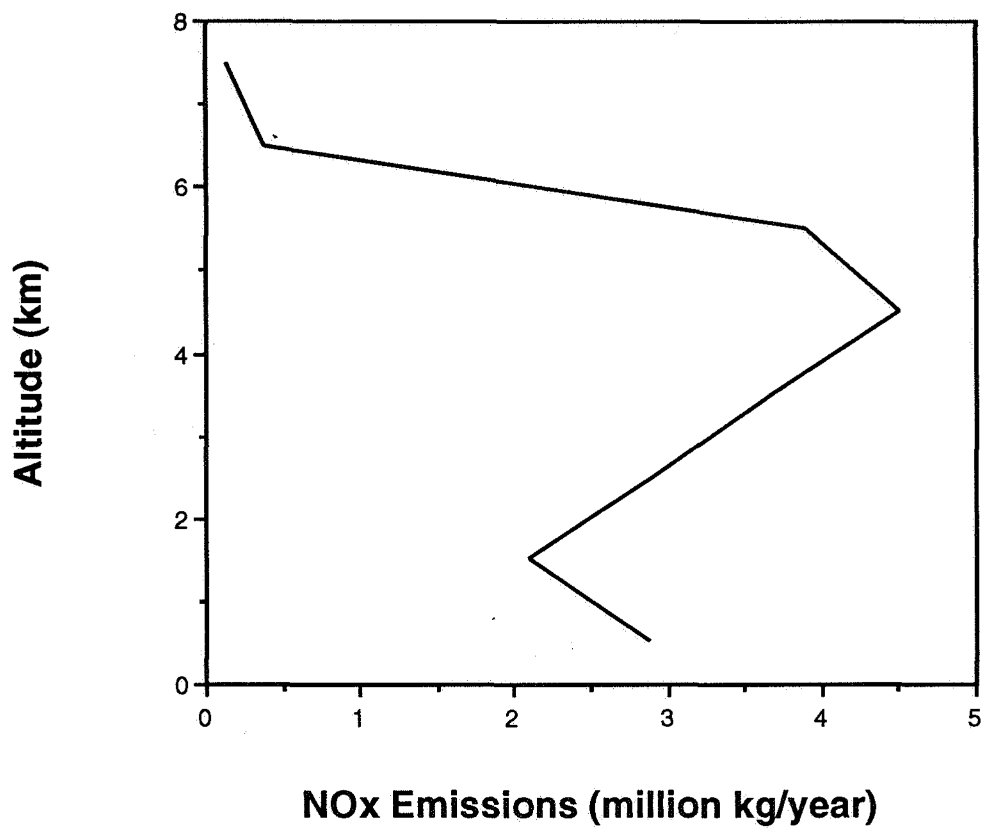


Figure 5-6. NOx emissions as a function of altitude for the 1990 scheduled turboprop aircraft fleet (summed over latitude and longitude).

The 1990 turboprop aircraft fleet flew mostly in the Northern Hemisphere at latitudes between 30° and 60° North. This is shown in Figure 5-7, where fuel burned is plotted as a function of latitude.

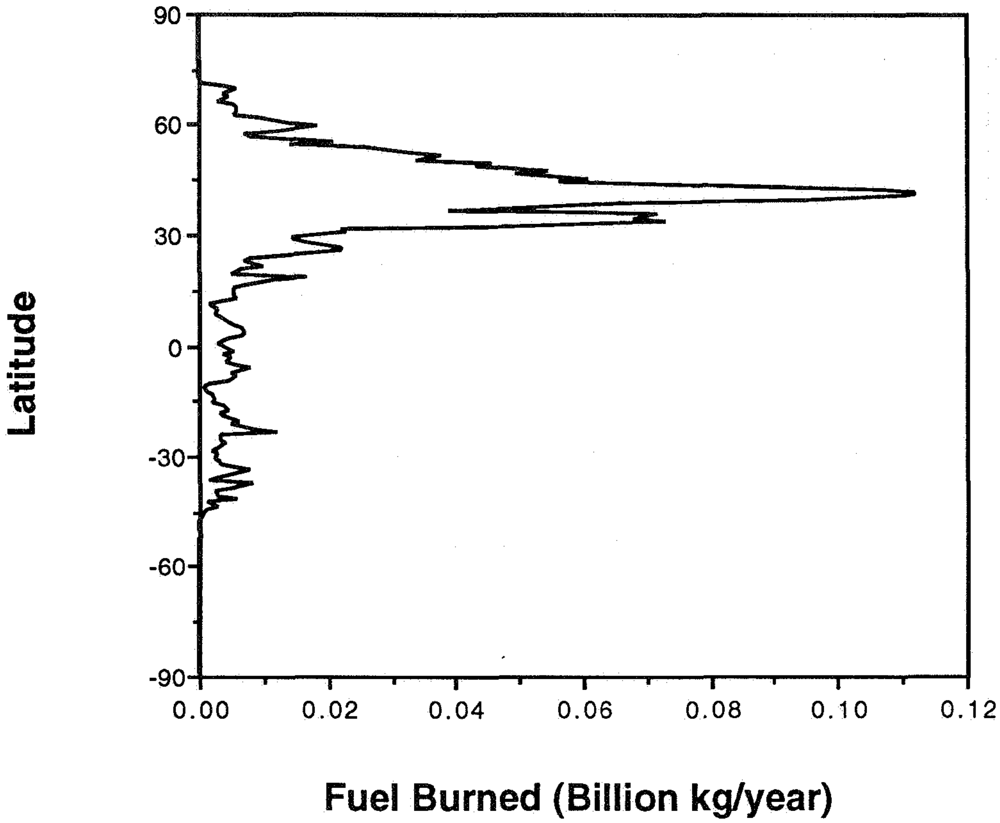


Figure 5-7. Fuel burned as a function of latitude for the 1990 scheduled turboprop aircraft fleet (summed over altitude and longitude).

5.3 Validation Tests

In 1990, the U.S. airlines reported to the government on DOT-Form 41 their total jet fuel usage, number of departures, and average route distance flown for specific aircraft. Using the GAEC code, Boeing calculated the scheduled traffic for each of these airlines for selected aircraft reported (Boeing 727-200 and 747). The results are summarized in Table 5-5. The calculated total fuel burn for all the airlines taken together appears to be about 9% lower than reported. The model uses about 6% more departures than reported as the annual average by the airlines. The fuel/trip is calculated to be about 14–17% lower than reported, since it undercounts the fuel usage and overcounts the departures.

In general, the agreement appears to be quite good and the differences arise both from simplified assumptions about the aircraft operation and the assumption that one week of departure data could be used to represent the annual average. The modeling calculation did not consider the effects on fuel consumption of airport congestion, diversion due to weather, auxiliary power unit utilization, or air traffic control. It assumed that aircraft were flown according to engineering design handbook rules with only the necessary amount of fuel plus reserves; in reality however, aircraft do not refuel at every landing and may carry more extra fuel than required by the U.S. Federal Aviation Authority (FAA).

Table 5-5. Comparison of calculated 1990 fuel burned with airline reported fuel burned for two aircraft types (Boeing 727-200 and 747)

AIRLINE	Scenario Model DAILY FUEL (lb)	Scenario Model DAILY DIST (nmi)	Scenario Model DAILY TRIPS	AIRLINE REPORTS DAILY FUEL (lb)	AIRLINE REPORTS DAILY DIST (nmi)	AIRLINE REPORTS DAILY TRIPS	% Diff Fuel	% Diff Distance	% Diff Departures	% Diff Fuel/mi	% Diff Fuel/trip
727-200											
AA	10,493,674	447,330	799.0	9,743,759	401,677	584	7.7%	11.4%	36.8%	-3.3%	-21.3%
CO	5,779,901	259,126	312.0	5,939,353	265,134	330	-2.7%	-2.3%	-5.5%	-0.4%	2.9%
DL	10,242,837	444,139	735.0	11,903,281	493,531	784	-13.9%	-10.0%	-6.3%	-4.4%	-8.2%
EA	3,267,819	142,311	233.0	3,896,787	162,505	235	-16.1%	-12.4%	-0.9%	-4.2%	-15.4%
NW	5,021,549	220,887	292.0	5,173,984	221,141	272	-2.9%	-0.1%	7.4%	-2.8%	-9.6%
PA	3,724,560	150,437	323.0	4,878,241	186,024	347	-23.6%	-19.1%	-6.9%	-5.6%	-18.0%
TW	3,778,249	161,967	284.0	4,105,429	164,484	238	-8.0%	-1.5%	19.3%	-6.5%	-22.9%
UA	6,923,548	301,352	487.0	8,229,635	340,652	473	-15.9%	-11.5%	3.0%	-4.9%	-18.3%
US	2,329,205	93,807	208.0	2,813,877	104,473	201	-17.2%	-10.2%	3.5%	-7.8%	-20.0%
TOTALS	**51,561,342**	**2,221,356**	**3673.0**	**56,684,346**	**2,339,621**	**3464**	-9.0%	-5.1%	6.0%	-4.2%	-14.2%
747 Comparison:											
NW(747-200)	8,868,421	184,091	76.0	10,834,547	210,086	73	-18.1%	-12.4%	4.1%	-6.6%	-21.4%
NW (747-400)	2,482,888	56,588	19.4	1,811,760	39,083	11	37.0%	44.8%	76.6%	-5.4%	-22.4%
PA(747-200)	7,799,309	171,264	58.6	9,249,919	184,727	58	-15.7%	-7.3%	1.0%	-9.1%	-16.5%
UA(747-200)	6,172,692	132,480	42.6	5,802,826	119,772	36	6.4%	10.6%	18.3%	-3.8%	-10.0%
UA(747-SP)	2,329,874	55,602	15.4	2,533,294	59,364	14	-8.0%	-6.3%	10.2%	-1.8%	-16.5%
TOTALS	**27,653,184**	**600,025**	**212.0**	**30,232,346**	**613,032**	**192**	-8.5%	-2.1%	10.4%	-6.5%	-17.2%

5.4 1990 Generic Fleet Analysis

The engineering data files used in the calculation of the 1990 scheduled airliner and cargo scenario contain detailed information which is considered proprietary by the Boeing Company. In order to provide non-proprietary data that could be used by NASA for their own tests, a 1990 generic database was constructed based on the performance curves of existing aircraft. The classification of airplanes and the performance characteristics of these generic airplanes were determined using fleet data from the Boeing marketing group and performance data from the predominant airplanes within the fleet classes. Eight generic classes of airplanes were identified. These classifications of 1990 fleet airplanes within the generic fleet are shown in Table 5-6.

Table 5-6. Aircraft types included in the construction of the 1990 "generic" database.

Generic Class	Real Aircraft	
1990.SST	Concorde	
P080	727-100_JT8D-9	DC9-10+20+30_JT8D
	BAC111_SPEY-512	FOKKER-100_TAY-650
	BAE146_ALF502	FOKKER-28_SPEY-555
	CARAVELLE-10B_JT8D	TU134_JT8D-7
P120	727-200_JT8D-9	DC9-40+50_JT8D
	737-200_JT8D-9	MD-87_JT8D-217
	737-200_JT8D-15	TRIDENT_JT8D-7
	737-300+400+500_CFM56	YAK-40+42_JT8D-7
	DASSMR_JT8D-7	
P180A	707-320B-C_JT3D-7	MD-82_JT8D-217
	727-200_JT8D-15	TU154_JT8D-15
	IL-62_JT3D-7	
P180B	757-200_PW2000	DC8-63_JT3D
	757-200_RB211	DC8-71_CFM56-B1
	A320-200+300_CFM56-5-A1	
P250	747SP_JT9D-7	767-300+ER_PW4060
	747SP_RB211	767-300ER_RB211
	767-200+ER_CF6-80A	A300-600+ER_CF6-80C2
	767-200+ER_JT9D-7R4	A300-B2+B4_CF6-50C2
	767-200+ER_PW4000	DC10-10_CF6-6D
	767-200+ER_CF6-80C2	DC10-30_CF6-50E2
	767-300+ER_CF6-80C2	L1011_RB211
	767-300+ER_JT9D-7R4	A310-200+300_CF6-80A
P350	747-100+200_JT9D-7A	747-200_JT9D-7R4G2
	747-100+200_CF6-50E2	747-200_RB211
	747-200_JT9D-7J	IL-86_RB211
	747-200_JT9D-7Q	
P500	747-300_CF6-50E2	747-400_CF6-80C2
	747-300_CF6-80C2	747-400_PW4056
	747-300_JT9D-7R4G2	747-400_RB211
	747-300_RB211	

The base performance data for the predominant airplane in each class were selected to represent the performance data of the generic class. The predominant airplane was defined as the airplane that had the greatest global fuel burn relative to all airplanes within that particular class during the year 1990. These base performance data were then adjusted using a weighting factor accounting for global and local performance characteristics of the airplanes within the generic classes. The local performance factors were determined by flying the aircraft of a given type on a mission typical of those flown by that aircraft class. Only the major contributors to total fuel burn within each class were included in the calculation of the weighting factors. The performance weighting factors were calculated as follows:

$$\textbf{factor} = \frac{\sum_{i=1}^{n} L_i \times G_i}{L_c \times \sum_{i=1}^{n} G_i}$$

where

L_i = local fuel, NO_x, HC, or CO values of each airplane within the generic class.

G_i = the global fuel, NO_x, HC, or CO values of each airplane within the generic class.

L_c = the local fuel, NO_x, HC, or CO value of the base airplane representing the generic class.

Separate factors were calculated for fuel burned, NOx, hydrocarbon, and carbon monoxide emissions. Emissions were calculated for the complete generic 1990 fleet by "flying" each generic airplane on the OAG routes of all airplanes within the respective generic class using the generic airplane performance data and weighting factors.

The flight statistics for the different classes of aircraft are summarized in Table 5-7.

Table 5-7. Departure statistics for the 1990 generic aircraft fleet.

Aircraft	Total Daily Distance (nm)	Total Daily Departures	Average Route Distance (nm)
P080 (70-109 passengers)	2285725	7103	322
P120 (110-139 passengers)	6149028	14385	427
P180A (140-199 passengers)	5035063	8608	585
P180B (140-199 passengers)	1190433	1578	754
P250 (200-299 passengers)	4559831	3946	1156
P350 (300-399 passengers)	2705302	1187	2279
P500 (400+ passengers)	606528	233	2606
1990.SST	21024	7	3066

Table 5-8. Fuel burned, emissions (NOx, hydrocarbons, carbon monoxide), and emission indices for the different generic aircraft types, summed over altitude, latitude, and longitude.

Aircraft	Fuel (kg/year)	NOx (kg/year)	HC (kg/year)	CO (kg/year)	EI(NOX)	EI(HC)	EI(CO)
1990.SST	1.47E+08	2.23E+06	1.20E+06	9.07E+06	15.15	8.14	61.53
P080	5.91E+09	4.75E+07	1.81E+07	1.39E+08	8.04	3.07	23.53
P120	1.43E+10	1.47E+08	7.37E+06	8.45E+07	10.27	0.52	5.91
P180A	1.77E+10	1.65E+08	1.77E+07	6.45E+07	9.28	1.00	3.64
P180B	3.24E+09	4.23E+07	4.65E+06	1.69E+07	13.07	1.44	5.22
P250	2.46E+10	3.69E+08	1.79E+07	1.06E+08	15.03	0.73	4.31
P350	2.07E+10	3.19E+08	2.91E+07	9.75E+07	15.43	1.41	4.72
P500	4.49E+09	6.64E+07	7.83E+06	1.54E+07	14.78	1.74	3.44
Total	9.11E+10	1.16E+09	1.04E+08	5.33E+08	12.72	1.14	5.85

The fuel burned and emissions for the different generic classes are given in Table 5-8. As might be expected, representing the entire fleet of aircraft with only eight generic types is less accurate than using the actual aircraft types in service. A comparison of the differences between the calculated fuel burned and emissions calculated using the database of 58 jet airliners and the eight 1990 generic classes is shown in Table 5-9. For this calculation, the results for the detailed calculation using 58 jet aircraft types were summed into classes and used as the reference in the comparison with the generic calculation.

As Table 5-9 shows, the generic description does a good job of accounting for global fuel burned, but there are errors of 10–15% for some aircraft types. Similarly globally calculated NO_X emissions appear to be accounted for to within about 10%. Hydrocarbon and carbon monoxide emissions are much more poorly accounted for in the generic calculations.

Table 5-9. Comparison of the globally summed fuel burned, emissions, and emission indices for the 1990 generic database relative to that calculated using actual 1990 aircraft.

Aircraft	Fuel	NOx	HC	CO	EI(NOX)	EI(HC)	EI(CO)
1990.SST	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
P080	0.52%	6.65%	-32.84%	-132.64%	6.17%	-33.53%	-133.85%
P120	11.85%	7.86%	50.61%	21.31%	-4.53%	43.98%	10.73%
P180A	-0.66%	7.31%	58.44%	34.85%	7.91%	58.71%	35.27%
P180B	15.01%	0.71%	64.02%	40.84%	-16.83%	57.67%	30.40%
P250	-13.58%	-11.57%	18.93%	10.73%	1.78%	28.62%	21.40%
P350	1.28%	-1.33%	-14.42%	-21.19%	-2.64%	-15.90%	-22.77%
P500	0.02%	-7.06%	-103.53%	-10.49%	-7.08%	-103.57%	-10.52%
Total	-0.29%	-1.55%	23.95%	-3.10%	-1.26%	24.17%	-2.80%

The generic description involves grouping aircraft of similar size and range together as a class. This means that both old and new technology aircraft are grouped together and treated as one. Improvements in combustor efficiency have resulted in significant changes in the CO and HC emissions of aircraft engines. Thus, the generic categories do not do a very good job of accounting for these emissions. Since the new and old technology aircraft are not uniformly distributed between countries, there will be errors introduced in the geographical distribution of the emissions when generic categories are used.

In general, while the 1990 generic aircraft may be useful for certain parametric studies, there are significant errors introduced by trying to represent the diverse global aircraft fleet by just a few generic aircraft types; and this should be borne in mind by users.

6. Year 2015 Subsonic Aircraft Scenarios

For year 2015, passenger demand was projected by averaging regional growth rates predicted by the Boeing and McDonnell Douglas market research groups as described in Section 2. The projected growth rates and revenue passenger miles by region were summarized in Table 2-2. 1991 was used as a base year for forecasting purposes It was assumed that the airline networks will be the same in 2015 as in 1991 and that airlines will operate with the same average load factors. In order to calculate the projected emission inventories due to subsonic aircraft, it is necessary to project the distribution between different sizes of aircraft and future performance and emission characteristics. Emission scenarios were calculated for cases with and without a 500 HSCT fleet in order to provide a reference case for atmospheric assessment calculations.

6.1 Distribution between Aircraft Types

In order to balance airplane size growth and airplane departures (flight frequency) growth, the initial calculations of 2015 scheduled available seats used the common growth rates, while the 2015 scheduled departures used 50% of the common growth rate (i.e., the airplanes are projected to get bigger on average). Future aircraft were grouped into ten generic passenger sizes (see Table 6-1).

Table 6-1. Classes of "Generic" Subsonic Passenger Aircraft Used in the 2015 Scenario Construction

Class	Seating Capacity	Average Seats
TBP (turboprop)	0 - 49	30
P060	50 - 69	60
P080	70 - 109	85
P120	110 - 139	120
P180	140 - 199	170
P250	200 - 299	250
P350	300 - 399	350
P500	400 - 599	500
P700	600 - 799	700
P900	> 800	900

Estimation of the airplane size and frequency requirements by city-pair market for the year 2015 requires that two elements be forecast:

- Total number of seats required by each city-pair market.
- Total number of departures required by each city-pair market.

The target minimum number of departures for city pairs in each region (as shown in Table 6-2) was used, based on a reasonable level of service and at least two competitors in each market.

Table 6-2. Target Departure Levels

Market	Target Weekly Frequencies
Domestic Markets	112
U.S. Domestic	
Europe Domestic & Intra Europe	
Japan Domestic	
Intra Regional	98
Asia/Oceania	
Indian Subcontinent	
Latin America	
Long Range	56
North America-Asia	
North America-Europe	
Europe-Asia	
All other	14

The calculation of the actual level of departures for each city pair and of the size of the airplanes assigned to the city pair are based on the forecast values of seats and departures from the initial calculation outlined above, the departure target levels of Table 6-2, and the sizes of the airplanes which can be assigned to the city pair. Figure 6-1 outlines the process used in assigning airplanes and calculating city pair departures:

(1) The initial estimate of average airplane size is calculated from the forecast of total seats required for the city pair and departures in year 2015.

(2) The initial average size estimate is compared to the average size in the base year of 1991. If initial average size in 2015 > 1991 average size, then:

Path A

(3) The initial calculated value of departures is compared with the target departure level. If initial calculated departures > target level, then:

   (6) "Generic" airplanes are assigned to the city pair such that the average size of the airplane assigned is greater than the initial average size.

   (7) City pair departures are recalculated based on the assigned "generic" airplane size.

(2) The initial average size estimate is compared to the average size in the base year of 1991. If initial average size in 2015 < 1991 average size, then:

Path B

(4) Year 2015 average airplane size is set equal to year 1991 average airplane size, and:

   (6) "Generic" airplanes are assigned to the city pair such that the average size of the airplane assigned is greater than the initial average size.

   (7) City pair departures are recalculated based on the assigned "generic" airplane size.

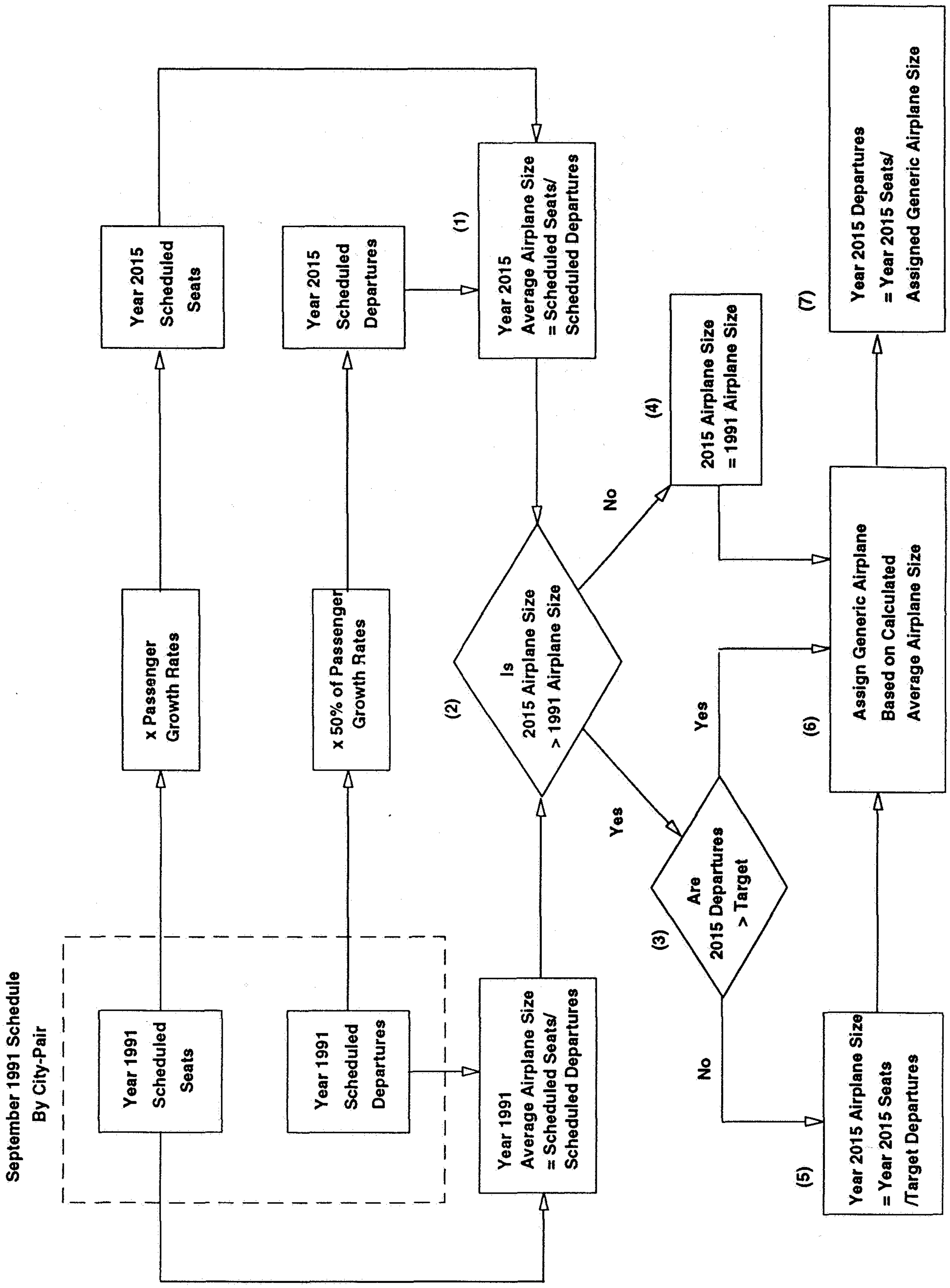


Figure 6-1. Flow chart of Seats and Departures Forecast Methodology

Figure 6-2 compares the available seat mile (ASM) distribution by generic size for the passenger airplane in the September 1991 schedule data and the NASA Emission Study Forecast for the year 2015 (based on the Boeing/McDonnell Douglas "common" growth rates, described in section 2). The latter forecast is shown with and without the presence of a fleet of 500 Mach 2.4 300-passenger HSCTs. A target HSCT fleet of 500 airplanes could consume about 12% of the year 2015 available seat miles.

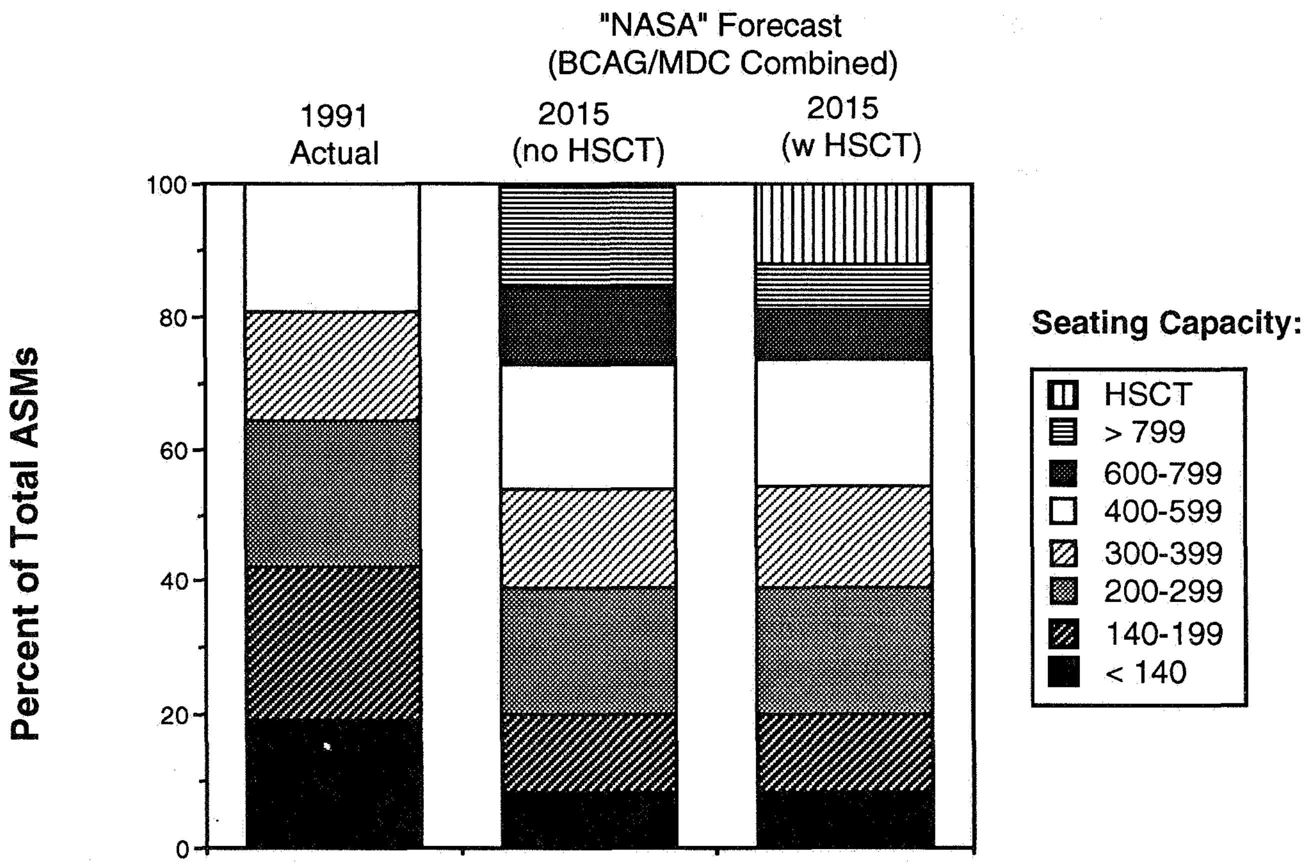


Figure 6-2. Passenger available seat mile distribution between different size aircraft for September 1991 and the NASA study forecast for 2015 (with and without an HSCT fleet).

6.2 Cargo Fleet Projection

The process for estimating the frequencies and aircraft size for cargo airplanes was the same as for the passenger airplanes except:

- Tons were used as a measure of capacity.
- Tons required were assumed to increase at 6.3% per year for all markets.
- Frequencies were assumed to increase at 4.0% per year for all markets.

The five classes of generic cargo aircraft are shown in Table 6-3.

Table 6-3. Classes of "Generic" Subsonic YR 2015 Cargo Airplane Used in the 2015 Scenario Construction

Class	Capacity (Tons)	Average (Tons)
C005	0 - 5	3.0
C010	5 - 10	15.0
C040	20 - 40	30.0
C080	40 - 80	60.0
C160	> 80	120.0

Figure 6-3 shows the resulting Available Ton Mile (ATM) distribution for the September 1991 schedule and the 2015 forecast results. As with the passenger fleet there is a shift to larger capacity airplanes. The growth in cargo demand plus the shift to larger airplanes result in a majority of the freighter departures being in aircraft of more than 40 ton capacity (DC-10/767 size airplanes).

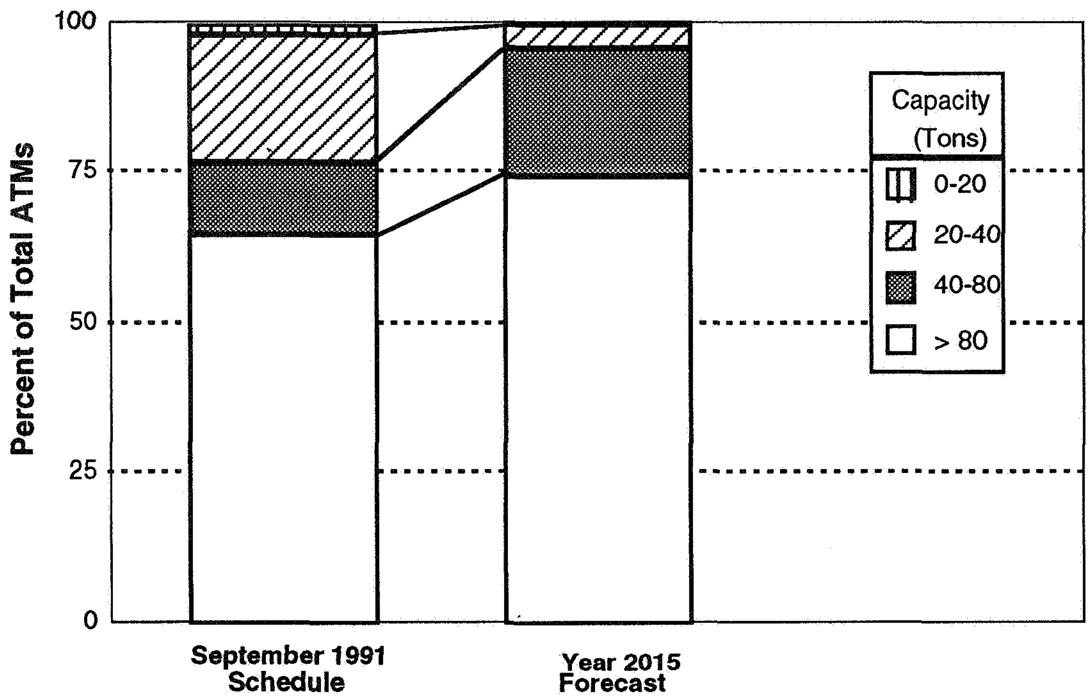


Figure 6-3. Cargo aircraft size distributions for 1991 and forecast for 2015.

6.3 2015 Aircraft Technology

Baseline 1990 airplane performance data and engine performance data were used as the basis for the analysis of each class of airplane in the 2015 fleet. One modern 1990 airplane, of the 57 subsonic aircraft/engine combinations described in section 3, was selected to represent each class of projected year 2015 airplane. Since there are no airplanes in the 1990 category for the two largest classes, P700 and P900, the fuel usage for the 1990 P500 category aircraft was scaled by the factors 1.4 and 1.5 relative to the largest known 1990 aircraft, respectively, to account for size. Technology improvement factors were applied to each airplane to account for estimated improvements in fuel burn and emissions for airplanes entering service between 1990 and 2015. Based on a Boeing marketing analysis, a year 2015 fleet would be composed of 50% airplanes built before 2005 and 50% airplanes built after 2005. The technology improvement factors were calculated assuming that the entire fleet would be "state of the art" for the year 2005.

Estimating the fuel flow improvement factor was a two-step process. First, the baseline airplane fuel flow was corrected to 1990 technology and then corrected again to reflect 2005 technology. The 1990 correction is based on the assumption that turbofan engines of all thrust ratings and equal technology will have approximately equal fuel flow to thrust ratios at maximum power. The improvement factor varies between classes, in part, because the age of the baseline aircraft differs from class to class. The fuel flow factor, wff, was calculated for each airplane as follows:

```
wff = fft(airplane)/fft(best standard in 1990)
```

where fft is the ratio of fuel flow for the particular airplane to the thrust at maximum power. An additional 2% reduction in fuel flow, wf, was used to reflect improvements for 2005. The corrected fuel flow, wfc, was thus obtained as follows:

```
wfc = wf(airplane) x wff x 0.98.
```

Engine emissions improvement factors were estimated based on known differences between older technology engines and new modern engines. Basically, the emissions characteristics were expected to improve to 1990 "state-of-the-art". The technology improvement factors used are summarized in Table 6-4.

Table 6-4. Technology Improvement Factors for 2015 Aircraft Relative to 1990 Technology

Generic Airplane	Fuel Flow Factor	NO_x factor	HC factor	CO factor
PTBP	1.00	1.00	1.00	1.00
P060	0.49	0.60	0.70	0.50
P080	0.69	0.70	0.60	0.70
P120	0.71	0.70	0.60	0.70
P180	0.75	0.70	0.60	0.70
P250A	0.87	0.60	1.00	1.00
P250B	0.86	0.70	0.60	0.70
P350	0.95	0.70	1.00	1.00
P500	0.86	0.70	0.60	0.70
P700	1.19*	0.70	1.00	1.00
P900	1.28*	0.70	1.00	1.00
C005	0.69	0.70	0.60	0.70
C010	0.75	0.70	0.60	0.70
C020	0.71	0.70	0.60	0.70
C040	0.87	0.60	1.00	1.00
C080	0.86	0.70	0.60	0.70
C160	0.86	0.70	0.60	0.70

* includes sizing effect

6.4 2015 Scheduled Jet Passenger Traffic Results

The total daily distances flown for each aircraft type are shown in Table 6-5 for the case where no HSCT fleet exists. For the year 2015 scenarios, a total of 17,123 city pairs were include with flights between 1,969 cities.

Table 6-5. Departure Statistics for the 2015 Scheduled Jet Passenger Fleet (no HSCT fleet exists)

Aircraft	Total Daily Distance (nm)
P060 (50-69 passengers)	1896384
P080 (70-109 passengers)	4689407
P120 (110-139 passengers)	8273926
P180 (140-199 passengers)	14151241
P250A (200-299 passengers)	9242938
P250B (200-299 passengers)	6906331
P350 (300-399 passengers)	9297091
P500 (400-499 passengers)	8320398
P700 (500-799 passengers)	3710548
P900 (> 800 passengers)	3888681

The fuel burned, emissions, and global average emission indices for the projected 2015 subsonic airliner scenario, assuming no HSCT fleet exists, are summarized by aircraft type in Table 6-6.

The fuel burned and emissions as a function of altitude (summed over latitude and longitude) are tabulated in Table E-8 in Appendix E.

Table 6-6. Globally Computed Fuel Burned, Emissions, and Emission Indices by Aircraft Type for 2015 Scheduled Subsonic Airliners if no HSCT Fleet Exists

					Globally Averaged Emission Indices		
File	**Fuel (kg/yr)**	**NO_x (kg/yr)**	**HC (kg/yr)**	**CO (kg/yr)**	**EI (NO_x)**	**EI (HC)**	**EI (CO)**
P060	2.63E+09	1.49E+07	1.47E+06	1.45E+07	5.66	0.56	5.50
P080	8.67E+09	6.84E+07	2.91E+06	6.59E+07	7.88	0.34	7.60
P120	1.42E+10	1.04E+08	8.02E+06	1.25E+08	7.37	0.57	8.85
P180	2.35E+10	1.73E+08	5.81E+06	1.23E+08	7.39	0.25	5.25
P250A	2.49E+10	2.15E+08	1.64E+07	1.63E+08	8.64	0.66	6.56
P250B	2.10E+10	1.54E+08	1.39E+07	7.59E+07	7.33	0.66	3.61
P350	4.32E+10	4.53E+08	1.52E+07	1.61E+08	10.49	0.35	3.72
P500	5.25E+10	4.88E+08	1.86E+07	2.23E+08	9.31	0.35	4.26
P700	3.15E+10	3.61E+08	5.11E+06	6.84E+07	11.48	0.16	2.17
P900	2.29E+10	2.06E+08	4.55E+06	6.52E+07	9.01	0.20	2.85
Total	2.45E+11	2.24E+09	9.20E+07	1.09E+09	9.14	0.38	4.43

A fleet of 500 Mach 2.4 HSCTs has been calculated to carry 386,800 passengers/day. This passenger demand would then be displaced from the subsonic airliners; so a scenario of these modified subsonic airliner operations was calculated. The results for the projected 2015 subsonic scenario, assuming an HSCT fleet exists, are summarized in Tables 6-7 and 6-8.

Table 6-7. Departure Statistics for the 2015 Scheduled Subsonic Jet Passenger Fleet (HSCT fleet exists)

Aircraft	Total Daily Distance (nm)
P060 (50-69 passengers)	1896384
P080 (70-109 passengers)	4689407
P120 (110-139 passengers)	8273926
P180 (140-199 passengers)	14115482
P250A (200-299 pass, short route)	9242938
P250B (200-299 pass, long route)	5395874
P350 (300-399 passengers)	8864087
P500 (400-599 passengers)	7836805
P700 (600-799 passengers)	2216309
P900 (> 800 passengers)	1578067

Table 6-8. Globally Computed Fuel Burned, Emissions, and Emission Indices by Aircraft Type for 2015 Scheduled Subsonic Airliners if 500 Mach 2.4 HSCTs were in Operation*

					Globally Averaged Emission Indices		
Aircraft	Fuel (kg/yr)	NO_x (kg/yr)	HC (kg/yr)	CO (kg/yr)	EI (NO_x)	EI (HC)	EI (CO)
P060	2.63E+09	1.49E+07	1.47E+06	1.45E+07	5.66	0.56	5.50
P080	8.67E+09	6.84E+07	2.91E+06	6.59E+07	7.88	0.34	7.60
P120	1.42E+10	1.04E+08	8.02E+06	1.25E+08	7.37	0.57	8.85
P180_w_hsct	2.34E+10	1.73E+08	5.81E+06	1.23E+08	7.39	0.25	5.26
P250A	2.49E+10	2.15E+08	1.64E+07	1.63E+08	8.64	0.66	6.56
P250B_w_hsct	1.64E+10	1.20E+08	1.16E+07	6.25E+07	7.32	0.71	3.82
P350_w_hsct	4.12E+10	4.33E+08	1.49E+07	1.57E+08	10.50	0.36	3.80
P500_w_hsct	4.97E+10	4.03E+08	4.97E+07	2.42E+08	8.11	1.00	4.86
P700_w_hsct	1.93E+10	2.27E+08	3.89E+06	5.02E+07	11.77	0.20	2.60
P900_w_hsct	9.43E+09	8.67E+07	2.43E+06	3.32E+07	9.19	0.26	3.52
Total	2.10E+11	1.85E+09	1.17E+08	1.04E+09	8.80	0.56	4.94

*1.00E + 08 = 1.00 x 10^8

The fuel burned and emissions as a function of altitude (summed over latitude and longitude) are tabulated in Table E-9 in Appendix E. A comparison of these results with the 1990 emission levels will be discussed in more detail in Section 7.

To illustrate the projected emission technology level, Figure 6-4 shows a plot of the emission indices for NOx, hydrocarbons, and carbon monoxide as a function of altitude for the scheduled passenger jet traffic in 2015 assuming no HSCT fleet is in operation. As for the 1990 results (Figure 5-1), the NOx emission indices are lower at cruise altitudes relative to the 2-4 km altitude range since the aircraft cruises at a lower thrust setting than during climb.

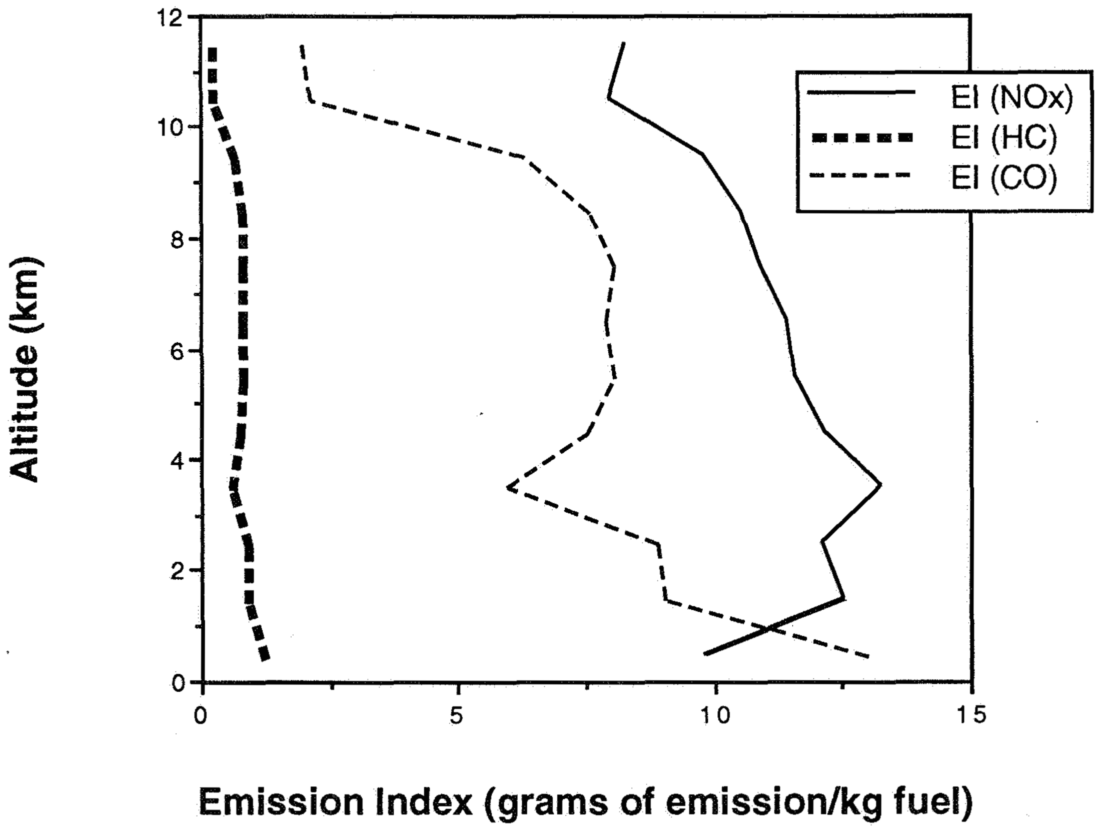


Figure 6-4. Emission indices for NOx, carbon monoxide, and hydrocarbons plotted as a function of altitude for the 2015 scheduled passenger jet traffic, assuming no HSCT fleet is in operation.

6.5 2015 Cargo Results

The total daily distances for the projected year 2015 cargo fleet are summarized in Table 6-9 for each cargo size category. The fuel burned and emissions for the projected 2015 scheduled cargo scenario are summarized in Table 6-10. The calculations indicate that fuel burned by scheduled cargo aircraft will only be about 2.3% of that used by scheduled airliners. The fuel burned, emissions, and emission indices for the 2015 cargo fleet are tabulated in Table E-10 in Appendix E.

Table 6-9. Departure Statistics for the 2015 Scheduled Jet Cargo Fleet

Aircraft	Total Daily Distance (nm)
C005 (5 ton cargo)	20423
C010 (10 ton cargo)	6296
C020 (20 ton cargo)	13268
C040 (40 ton cargo)	171890
C080 (80 ton cargo)	437030
C160 (> 80 ton cargo)	606722

Table 6-10. Globally Computed Fuel Burned, Emissions, and Emission Indices for 2015 Scheduled Jet Cargo Aircraft*

					Globally Averaged Emission Indices		
Aircraft	**Fuel (kg/year)**	**NO_X (kg/year)**	**HC (kg/year)**	**CO (kg/year)**	**EI (NO_X)**	**EI (HC)**	**EI (CO)**
C005	4.13E+07	3.28E+05	1.49E+04	3.38E+05	7.94	0.36	8.19
C010	1.16E+07	8.99E+04	4.04E+03	8.62E+04	7.72	0.35	7.41
C020	2.54E+07	1.95E+05	1.84E+04	2.76E+05	7.69	0.72	10.86
C040	4.57E+08	3.91E+06	2.91E+05	2.89E+06	8.56	0.64	6.34
C080	1.40E+09	1.10E+07	2.06E+06	9.87E+06	7.80	1.47	7.03
C160	3.71E+09	3.36E+07	1.17E+06	1.42E+07	9.07	0.32	3.84
Total	5.64E+09	4.91E+07	3.56E+06	2.77E+07	8.69	0.63	4.90

*1.00E + 08 = 1.00×10^8

6.6 2015 Turboprop Results

The 2015 turboprop analysis was completed using the 1990 medium sized turboprop performance data for all turboprop routes in the projected 2015 OAG. No technology improvement factors were applied to the data since it is uncertain how the fuel burn and emissions characteristics of these airplanes will change. A detailed analysis of future turboprop technology was not justified because the calculations for 1990 indicate that turboprops only consume 1.1% of the global jet fuel (see section 7). The departure statistics are summarized in Table 6-11. Turboprop air traffic between 7,171 city pairs was analyzed using 2,331 cities.

Table 6-11. Departure Statistics for 2015 Scheduled Turboprop Aircraft

Aircraft	Total Daily Distance (nm)	Total Daily Departures	Average Route Distance (nm)
PTBP (turboprops)	5,806,976	38,743	150

Global fuel usage by turboprops was calculated to be 4.14×10^9 kg/year, which is 1.7% of the fuel used by the projected 2015 airliners. (see Table 6-12)

Table 6-12. Globally Computed Fuel Burned, Emissions, and Emission Indices for 2015 Scheduled Turboprop Aircraft*

				Globally Averaged Emission Indices		
Fuel (kg/year)	NO_X (kg/year)	HC (kg/year)	CO (kg/year)	EI (NO_X)	EI (HC)	EI (CO)
4.14E+09	4.42E+07	7.27E+06	2.41E+07	10.68	1.76	5.83

*1.00E + 08 = 1.00×10^8

The fuel burned and emissions as a function of altitude (globally summed over latitude and longitude) for projected fleets of turboprop aircraft are tabulated in Table E-11 in Appendix E.

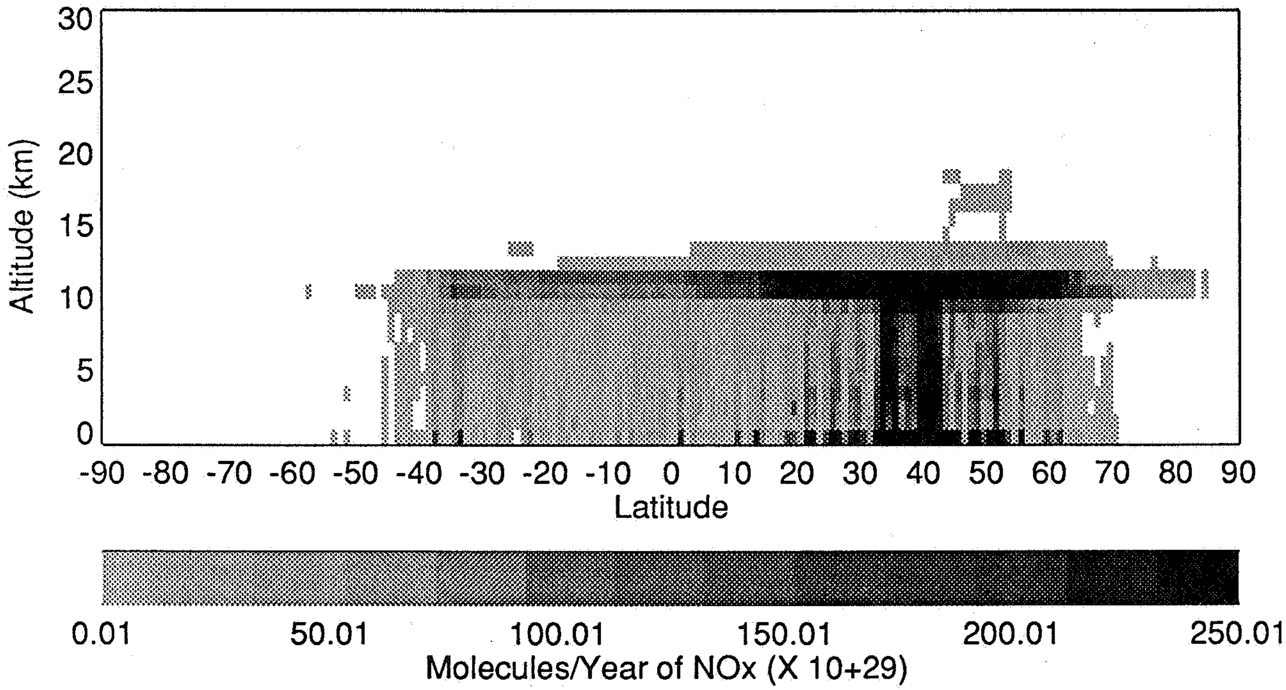
7. Analysis and Discussion

Three-dimensional inventories of fuel usage and exhaust emissions have been calculated for the different components (subsonic, HSCT, cargo, and turboprop) of the scheduled commercial air traffic fleet for 1990 and 2015. The enormous size and three-dimensionality of the data makes it difficult to display all features of the results. Instead, in most cases, the data have been summed over one or more dimensions to produce one-dimensional plots to illustrate various properties of the emissions distribution or aircraft characteristics.

The three-dimensional character can be seen in Figures 7-1 and 7-2, which show the NOx emissions as a gray scale plot as a function of altitude and latitude (top panels) and as a function of latitude and longitude (bottom panels) for both the 1990 scheduled air traffic (jet passenger, cargo, and turboprop) (Figure 7-1) and the 2015 scheduled air traffic (assuming no HSCT fleet is in operation) (Figure 7-2). In both cases, the peak emissions are calculated at northern mid-latitudes in the 10-13 km altitude band. For comparison, a similar plot for only the HSCT fleet was shown in Figure 4-6.

In order to understand the impact of aircraft emissions on the atmosphere, the total emissions from all aircraft sources must be considered. In this study, we have calculated those components due to scheduled commercial air traffic. In a parallel study, McDonnell Douglas calculated emissions for military, charter, and traffic not scheduled in the Official Airline Guide (intra former Soviet Union and China). The total of the Boeing and McDonnell Douglas work has been analyzed and discussed in Reference 4. It will not discussed in depth in this report.

In this section, the results for the different aircraft fleet components which contribute to the scheduled air traffic for both 1990 and 2015 will be summarized and discussed.



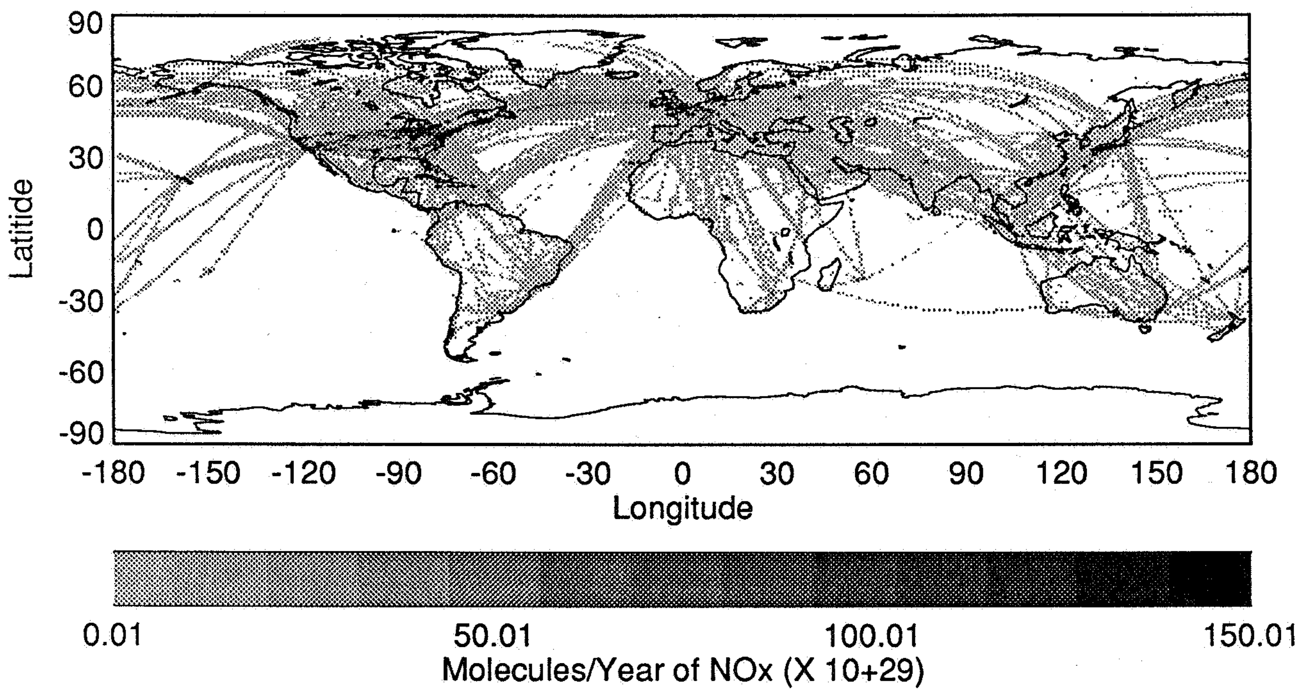
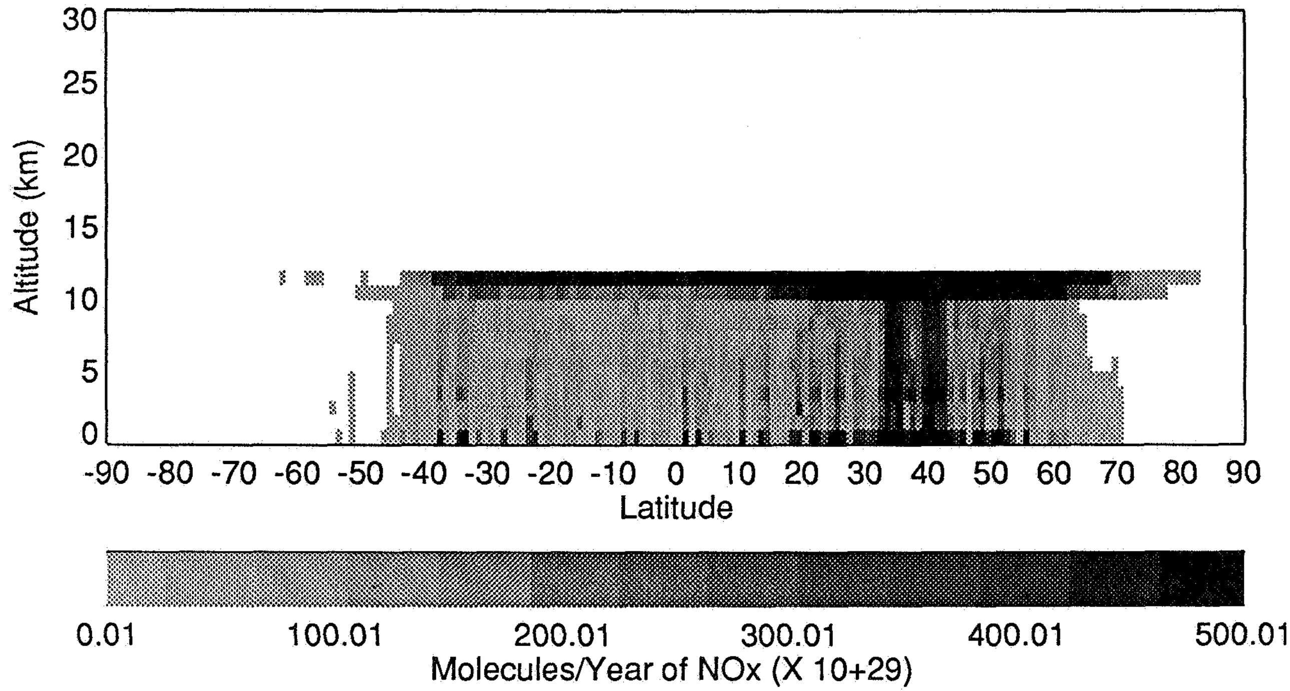


Figure 7-1. NOx emissions for 1990 scheduled air traffic (airliner, cargo, and turboprop) as a function of altitude and latitude (summed over longitude) (top panel) and as a function of latitude and longitude (summed over altitude) (bottom panel).



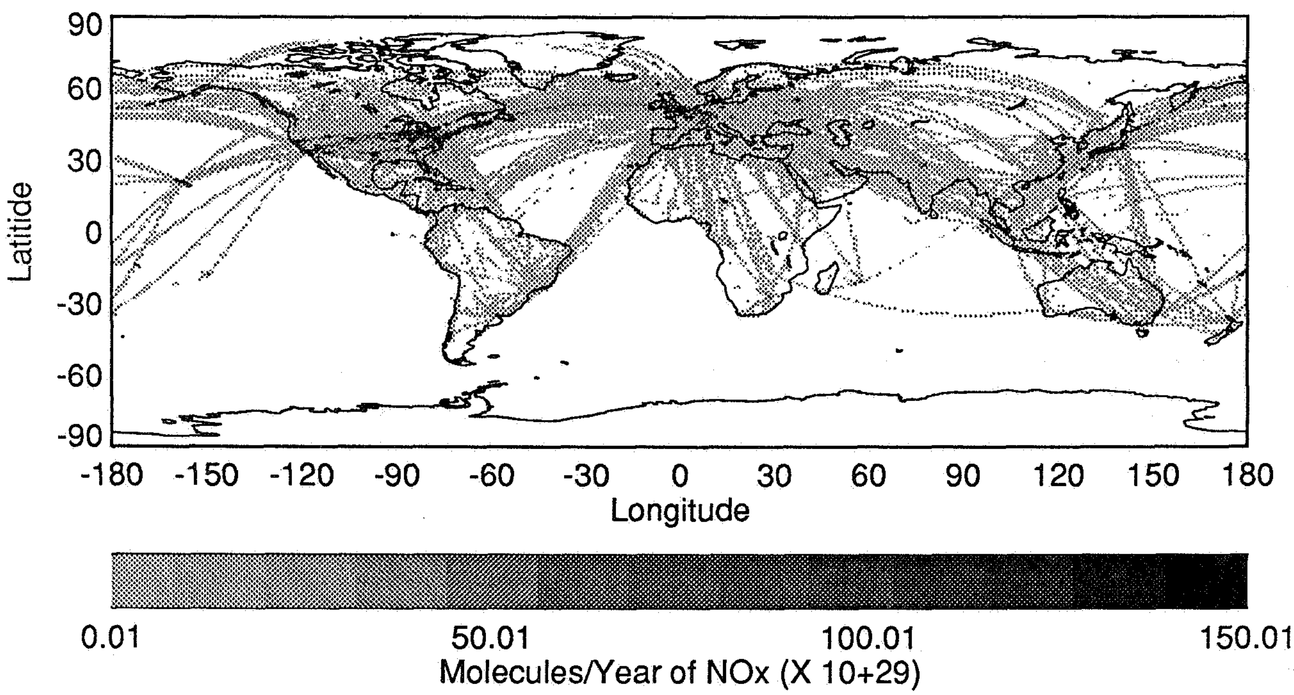


Figure 7-2. NOx emissions for projected 2015 scheduled air traffic (airliner, cargo, and turboprop) as a function of altitude and latitude (summed over longitude) (top panel) and as a function of latitude and longitude (summed over altitude) (bottom panel) assuming no HSCT fleet exists.

7.1 Summary of Results

The annual global fuel usage and emissions which have been calculated for the individual components of 1990 scheduled air traffic are summarized in Table 7-1. For this summary table and those that follow, the three-dimensional inventories have been summed over latitude, longitude, and altitude to yield the total global fuel usage and emissions. Also, shown in Table 7-1 are the totals for the combined scheduled passenger jet, turboprop, and cargo fleets.

Table 7-1. Summary of annual global fuel use, NOx, hydrocarbons, and carbon monoxide for the 1990 emission inventories.

	Fuel (kg/year)	NOx (kg/year)	HC (kg/year)	CO (kg/year)
1990 Scheduled Passenger Jet and Cargo Fleet	9.08E+10	1.14E+09	1.37E+08	5.17E+08
1990 Turboprop Fleet	1.99E+09	2.05E+07	1.11E+06	9.77E+06
Total 1990 Scheduled Passenger Jet, Turboprop, and Cargo Fleet	9.28E+10	1.16E+09	1.38E+08	5.27E+08

Note: NOx is given as gram equivalent NO_2

Using the fuel properties and emission indices presented in Sections 3.7-3.9 of this report, the annual global emissions for carbon dioxide, water vapor, and sulfur dioxide have been calculated from the fuel usage. These are summarized for the 1990 fleet in Table 7-2.

Table 7-2. Summary of annual global carbon dioxide, water vapor, and sulfur dioxide emissions for the 1990 emission inventories.

	CO_2 (kg/year)	H_2O (kg/year)	SO_2 (kg/year)
1990 Scheduled Passenger Jet and Cargo Fleet	2.87E+11	1.12E+11	7.27E+07
1990 Turboprop Fleet	6.27E+09	2.46E+09	1.59E+06
Total 1990 Scheduled Passenger Jet, Turboprop, and Cargo Fleet	2.93E+11	1.15E+11	7.42E+07

The annual global fuel usage and emissions for the component scenarios of the projected 2015 fleets are shown in Table 7-3, which include the HSCT fleets, subsonic fleets (with and without an HSCT fleet), and turboprop aircraft. The annual global carbon dioxide, water vapor, and sulfur dioxide emissions for the 2015 components are shown in Table 7-4 which uses the projected sulfur content of jet fuel as described in Section 3.9.

The year 2015 component scenarios have been summed to produce the different permutations of scheduled commercial fleets, both with and without HSCT fleets. The fuel usage and emissions for these are summarized in Table 7-5. Carbon dioxide, water vapor, and sulfur dioxide emissions are summarized in Table 7-6.

Further comparisons of the 2015 results with those of 1990 will be made in Section 7-2.

Table 7-3. Summary of annual global fuel use, NOx, hydrocarbons, and carbon monoxide for the 2015 individual component emission inventories.

	Fuel (kg/year)	NOx (kg/year)	HC (kg/year)	CO (kg/year)
<u>HSCT Scenarios:</u>				
Mach 2.4, EI=5 (500 HSCTs only)	7.64E+10	5.00E+08	2.83E+07	2.33E+08
Mach 2.4, EI=15 (500 HSCTs only)	7.64E+10	1.36E+09	2.83E+07	2.33E+08
Mach 2.0, EI=5 (500 HSCTs only)	7.87E+10	4.70E+08	2.75E+07	2.35E+08
Mach 2.0, EI=15 (500 HSCTs only)	7.87E+10	1.38E+09	2.75E+07	2.35E+08
<u>Subsonic Scenarios:</u>				
2015 Passenger Jet Fleet (no HSCT fleet exists)	2.45E+11	2.24E+09	9.20E+07	1.09E+09
2015 Passenger Jet Fleet (with 500 HSCT fleet)	2.10E+11	1.85E+09	1.17E+08	1.04E+09
2015 Cargo Fleet	5.64E+09	4.91E+07	3.56E+06	2.77E+07
2015 Turboprop Fleet	4.14E+09	4.42E+07	7.27E+06	2.41E+07

Note: NOx is given as gram equivalent NO_2

Table 7-4. Summary of carbon dioxide, water vapor, and sulfur dioxide emissions for the 2015 individual components of the emission inventories.

	CO_2 (kg/year)	H_2O (kg/year)	SO_2 (kg/year)
<u>HSCT Scenarios:</u>			
Mach 2.4, EI=5 (500 HSCTs only)	2.41E+11	9.45E+10	3.06E+07
Mach 2.4, EI=15 (500 HSCTs only)	2.41E+11	9.45E+10	3.06E+07
Mach 2.0, EI=5 (500 HSCTs only)	2.48E+11	9.73E+10	3.15E+07
Mach 2.0, EI=15 (500 HSCTs only)	2.48E+11	9.73E+10	3.15E+07
<u>Subsonic Scenarios:</u>			
2015 Passenger Jet Fleet (no HSCT fleet exists)	7.72E+11	3.03E+11	9.79E+07
2015 Passenger Jet Fleet (with 500 HSCT fleet)	6.62E+11	2.59E+11	8.39E+07
2015 Cargo Fleet	1.78E+10	6.98E+09	2.26E+06
2015 Turboprop Fleet	1.31E+10	5.12E+09	1.66E+06

Table 7-5. Summary of fuel use, NOx, hydrocarbons, and carbon monoxide for the total scheduled air traffic scenarios for 2015.

	Fuel (kg/year)	NOx (kg/year)	HC (kg/year)	CO (kg/year)
Total 2015 Scheduled Air Traffic without an HSCT fleet	2.55E+11	2.33E+09	1.03E+08	1.14E+09
Total 2015 Scheduled Air Traffic with a 500 Mach 2.4 HSCT fleet (EI(NOx)=5)	2.96E+11	2.44E+09	1.56E+08	1.32E+09
Total 2015 Scheduled Air Traffic with a 500 Mach 2.4 HSCT fleet (EI(NOx)=15)	2.96E+11	3.30E+09	1.56E+08	1.32E+09
Total 2015 Scheduled Air Traffic with a 500 Mach 2.0 HSCT fleet (EI(NOx)=5)	2.98E+11	2.41E+09	1.55E+08	1.32E+09
Total 2015 Scheduled Air Traffic with a 500 Mach 2.0 HSCT fleet (EI(NOx)=15)	2.98E+11	3.31E+09	1.55E+08	1.32E+09

Note: NOx is given as gram equivalent NO_2

Table 7-6. Summary of carbon dioxide, water vapor, and sulfur dioxide emissions for the total scheduled air traffic scenarios for 2015.

	CO_2 (kg/year)	H_2O (kg/year)	SO_2 (kg/year)
Total 2015 Scheduled Air Traffic without an HSCT fleet	8.03E+11	3.15E+11	1.02E+08
Total 2015 Scheduled Air Traffic with a 500 Mach 2.4 HSCT fleet (EI(NOx)=5)	9.34E+11	3.66E+11	1.18E+08
Total 2015 Scheduled Air Traffic with a 500 Mach 2.4 HSCT fleet (EI(NOx)=15)	9.34E+11	3.66E+11	1.18E+08
Total 2015 Scheduled Air Traffic with a 500 Mach 2.0 HSCT fleet (EI(NOx)=5)	9.41E+11	3.69E+11	1.19E+08
Total 2015 Scheduled Air Traffic with a 500 Mach 2.0 HSCT fleet (EI(NOx)=15)	9.41E+11	3.69E+11	1.19E+08

7.2 Comparison between 1990 and 2015

Air traffic is projected to grow significantly between 1990 and 2015. As a consequence, fuel usage and emissions from aircraft are expected to increase, even with some improvements in both efficiency and combustor technology.

Fuel usage by scheduled airliner and cargo aircraft in 2015 is projected to be about three times larger than 1990 levels. Global NO_x emissions from scheduled air traffic are projected to increase by about a factor of two from 1990 to 2015. By comparison, revenue passenger miles are projected to increase by a factor of about six, from 1203 billion in 1990 to 6883 billion in 2015 (based on the "common" forecast described in section 2 of this report).

The changes in NOx emissions are shown graphically in Figure 7-3. Emissions in 2015 from the scheduled aircraft fleet (passenger jet, cargo, and turboprop) are projected to be greater than in 1990 whether an HSCT fleet exists or not. An HSCT fleet displaces some of the subsonic fleet, resulting in fewer emissions 10-13 km altitude band but adds emissions in the lower stratosphere at 18-21 km flight altitudes.

Figure 7-4 shows that few changes are predicted between the altitude profiles of 1990 and 2015 subsonic fleets. Approximately 60% of the NOx emissions are calculated to occur above 10 km altitude. If a fleet of 500 Mach 2.4 HSCTs is in operation, approximately 15% of the NOx emissions occur above 13 km.

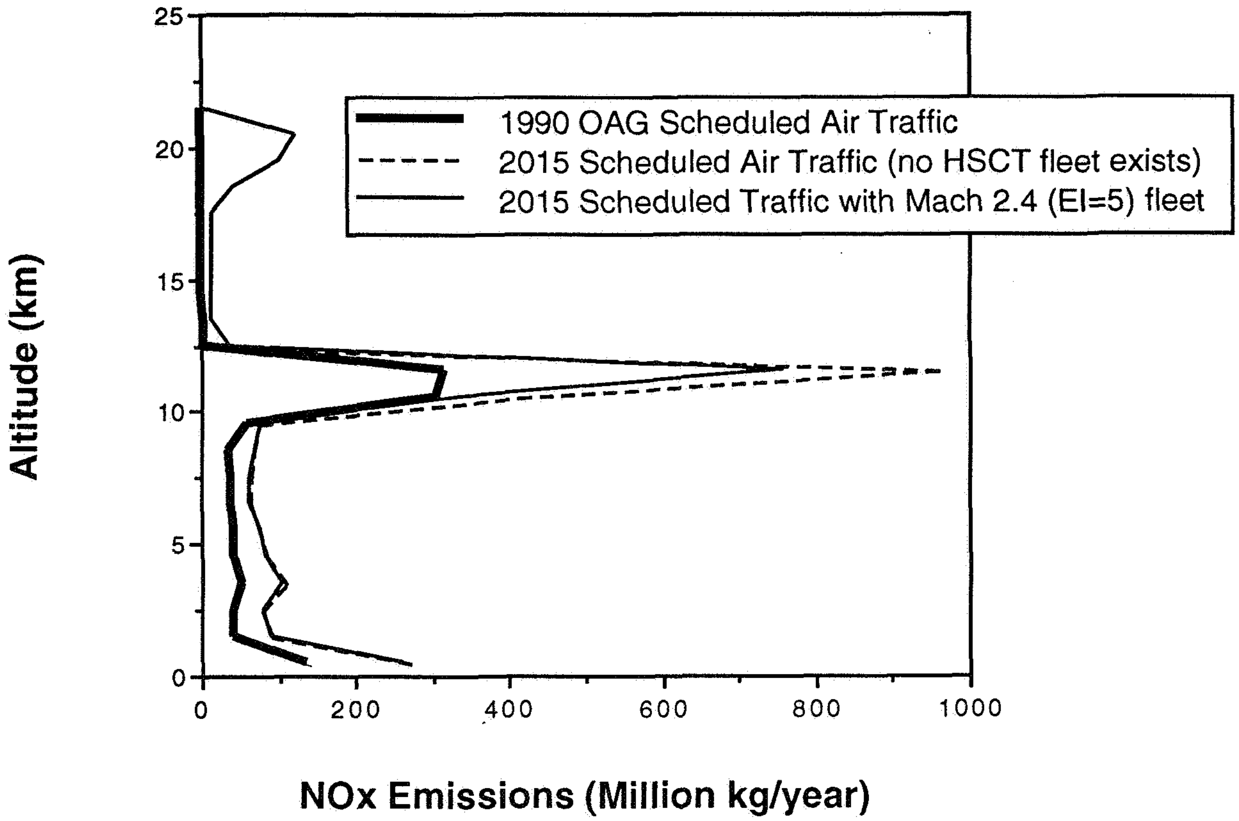


Figure 7-3. Annual NOx emissions as a function of altitude for 1990 OAG scheduled air traffic and projected 2015 scheduled air traffic, with and without 500 Mach 2.4 EI(NOx)=5 HSCTs.

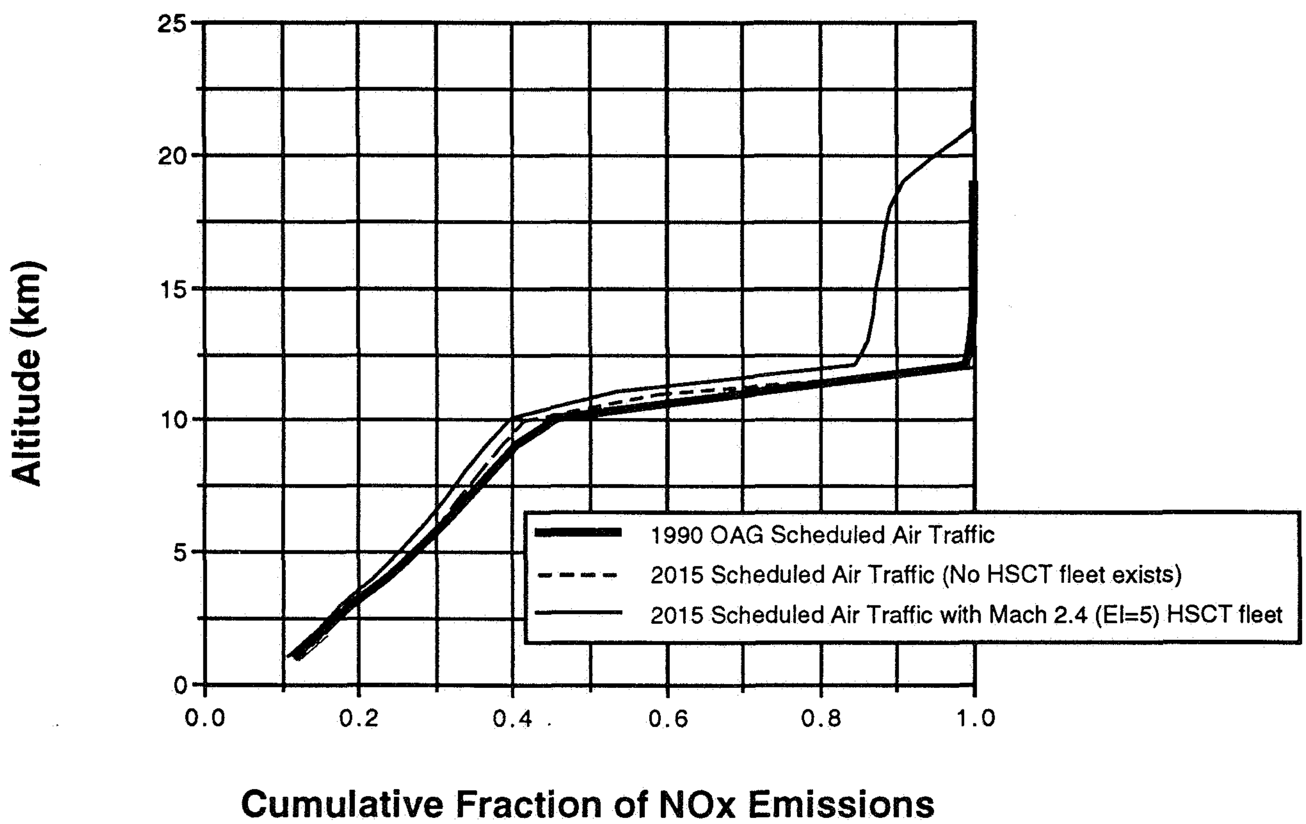


Figure 7-4. Cumulative fraction of NOx emissions as a function of altitude for 1990 OAG scheduled air traffic and projected 2015 scheduled air traffic, with and without 500 Mach 2.4 EI(NOx)=5 HSCTs.

Plots of fuel usage as a function of latitude (summed over altitude and longitude) (Figures 7-5 and 7-6) show that the largest relative increase is in the tropics and lower latitudes. In both 1990 and 2015, most air traffic is expected to occur in the northern hemisphere.

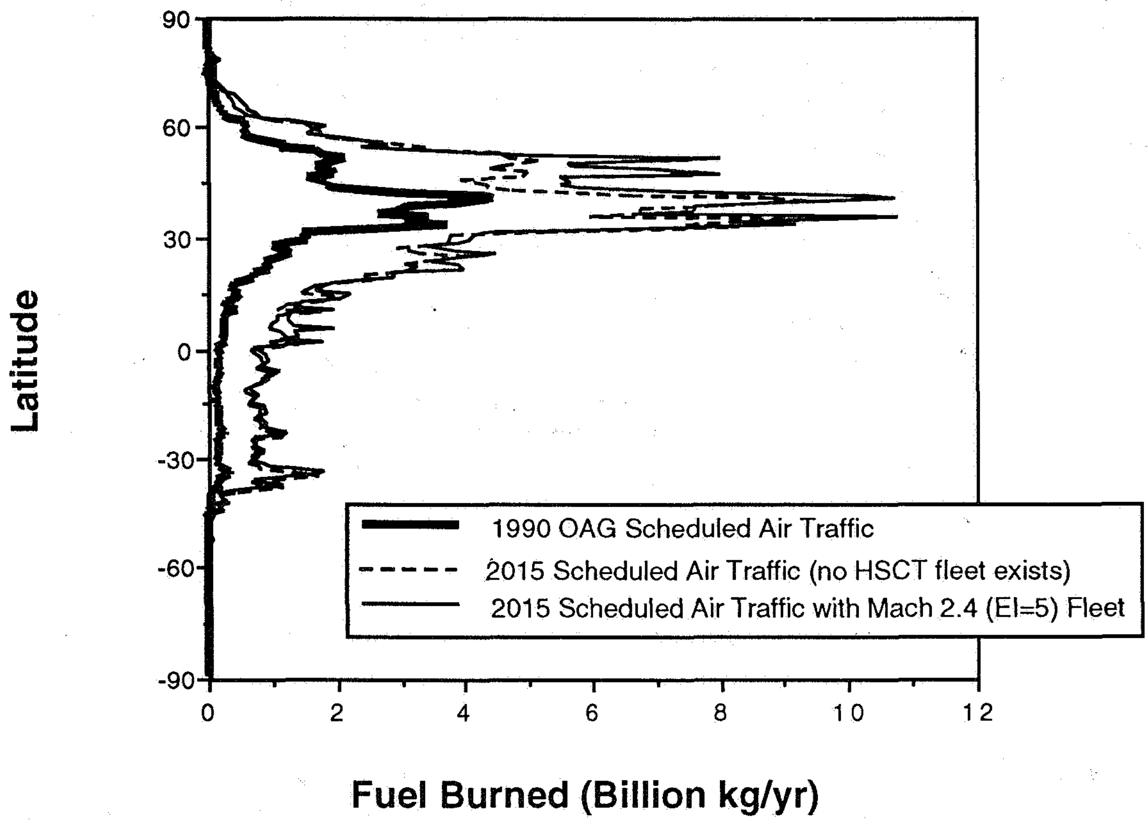


Figure 7-5. Annual fuel usage as a function of latitude for 1990 OAG scheduled air traffic and projected 2015 scheduled air traffic, with and without 500 Mach 2.4 EI(NOx)=5 HSCTs.

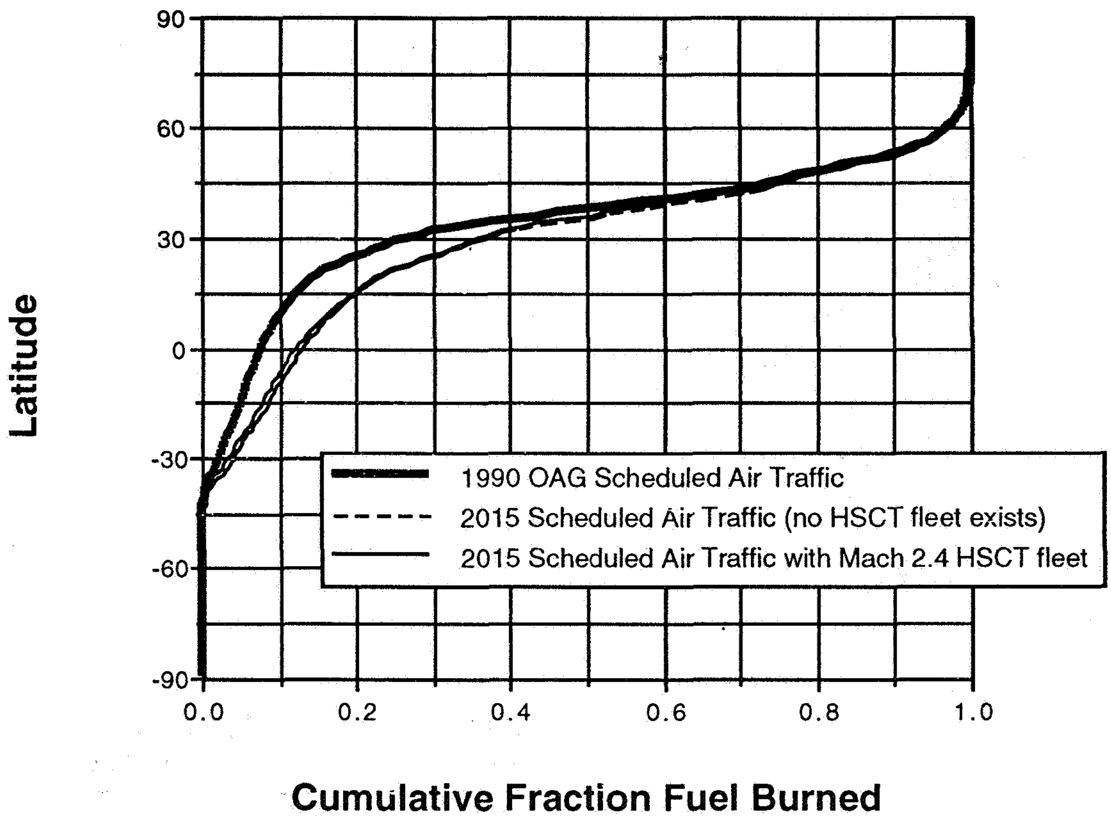


Figure 7-6. Cumulative fuel usage as a function of latitude for 1990 OAG scheduled air traffic and projected 2015 scheduled air traffic, with and without 500 Mach 2.4 EI(NOx)=5 HSCTs.

7.3 Comparison of 1990 results with reported jet fuel consumption

Total worldwide jet fuel consumption has been reported by the U.S. Department of Energy (Reference 13), while jet fuel consumption by civil aviation for 1990 has been published by the International Civil Aviation Organization (Reference 14). The difference between the total reported jet fuel consumption and the total jet fuel use by civil aviation provides some estimate of the military fuel use. These results and those of the calculated 1990 fuel burn for each of the individual AESA component emission scenarios are tabulated in Table 7-7.

Table 7-7. Comparison of Calculated 1990 Jet Fuel Usage with Reported Jet Fuel Use.

		Reported Fuel (kg/year)	Fraction of Total	Calculated Scenarios Fuel (kg/year)	Fraction of Reported World Use
Total World Jet Fuel Consumption (Ref. 13)		1.76E+11		1.34E+11	75.98%
World Civil Aviation Fuel Usage (Ref. 14)		1.37E+11			
	General Aviation (Ref. 14)	3.50E+09	1.99%	not included	not included
	Comm. Airlines (Ref.14)	1.33E+11	75.57%	1.08E+11	61.20%
	Scheduled Airliner and Cargo			9.08E+10	51.59%
	Scheduled Turboprop			1.99E+09	1.13%
	Charter			6.65E+09	3.78%
	Non-Scheduled Former Soviet Union			8.28E+09	4.70%
Non-Civil Usage (Military)		3.95E+10	22.44%	2.60E+10	14.77%

In table 7-7, the scenarios for charter, military, and non-scheduled former Soviet Union were calculated by McDonnell Douglas (References 4 and 15).

Approximately 76% of the world jet fuel consumption has been accounted for in the scenarios calculated by Boeing and McDonnell Douglas for 1990. General aviation was not considered in these calculations but is reported to account for only 2% of the world usage. (Reference 14) The calculations of scheduled passenger airline, scheduled cargo, scheduled turboprop, charter, and former Soviet Union account for 81% of the jet fuel use reported by ICAO for commercial operations (Reference 14). The military scenario is calculated to correspond to 66% of the non-civilian jet fuel use (the difference between the total world jet fuel consumption and the reported world civil aviation fuel use).

This agreement is quite good considering the number of simplifying assumptions that have been made in order to make the problem computationally tractable. In all of the scenarios, the aircraft were assumed to fly according to engineering design handbook rules along great circle routes between the city-pairs without accounting for diversions due to air traffic control, weather holds, airport congestion, and fuel use by auxiliary power units. Altitudes were calculated according to optimized performance rather than "step climbs" dictated by air traffic control. In addition, the calculations used May 1990 as representative of the annual average air traffic schedule for 1990. Both commercial and military air traffic in late 1990 were perturbed by the invasion of Kuwait by Iraq and the Gulf War.

Based on the comparisons reported in Section 5 for 1990 scheduled airline operations, (Table 5-5), the scheduled jet passenger and cargo scenario may have a systematic error of about 9% in the fuel usage. It is much more difficult to evaluate the accuracy of the military, charter, and non-OAG-scheduled flights in the former Soviet Union. In addition to uncertainties about the fuel burn and emissions technologies for these nonscheduled operations, there are large uncertainties about the flight frequencies and the type of equipment utilized.

In addition, for the nonscheduled air traffic, generic aircraft types were used to calculate the emission inventories. As was shown in earlier, there can easily be systematic errors associated with using performance and emissions characteristics of generic aircraft in the calculations, particularly if there is large variability in the technology within a given class of aircraft. This was shown for the generic 1990 aircraft described in Section 5.4, which were carefully constructed by linear combinations of actual aircraft performances. The errors may be even larger when such a detailed database is not available to guide the construction of the generic database. It is difficult to conclude at this time whether further refinements in these databases are needed, since the calculations have accounted for the majority of world jet fuel use.

It is also difficult to assess the accuracy of the reported jet fuel consumption. These databases are compiled from a variety of sources in many countries. We believe that the DOE database for jet fuel is based on refinery product output. Jet fuel can be used in place of diesel fuel for both ground transportation and home heating. In countries where fuel is at a premium, jet fuel may be used for a variety of purposes other than aviation; thus, the DOE reports may overestimate the worldwide jet fuel use for aviation. Similarly, we believe the ICAO numbers are derived from airline reports, the completeness and accuracy of which vary. As a result, an estimate for military use derived from the difference between the DOE total jet fuel use and the ICAO report of civil aviation use may not be valid.

A comprehensive critique of the refinery production of jet fuel and of the ICAO database would be a major project. Since the calculated jet fuel amounts in the current emissions database account for about 78% of the reported usage (including the calculated scenarios plus the ICAO value for general aviation), it is not clear that such a study is warranted at this time.

7.4 Conclusions and Recommendations

A detailed database of 1990, projected 2015 scheduled subsonic aircraft operations, and HSCT (Mach 2.0 and Mach 2.4) scenarios has been developed. Three-dimensional data files of fuel burned and emissions (NOx, hydrocarbons, and carbon monoxide) on a 1° latitude x 1° longitude x 1 km altitude grid were delivered electronically to the Upper Atmosphere Data Program (UADP) system at the NASA Langley Research Center.

The calculated results for 1990 scheduled air traffic have been compared to fuel use reported by the US airlines and appear to be about 9% lower. When the results reported here are combined with the non-scheduled (military, internal former Soviet Union, China, and charter) air traffic calculated by McDonnell Douglas and with the ICAO value for general aviation, the results account for 78% of the 1990 jet fuel consumption. Since the purpose of the database was to account for aircraft emissions globally at cruise altitudes, this is reasonably good agreement.

A number of simplifying approximations have been made in order to make the calculation of a global inventory tractable. These have included the following:

- Great circle routing, rather than air traffic controlled flights lanes.
- Cruise climb, rather than step climb.
- US Standard Atmosphere temperature profile with no winds
- No special procedures, flight holds, or circling near airports. Flights were calculated to takeoff and land in the direct line between the origin and destination.
- May 1990 was assumed to representative of the annual average for 1990.
- Fuel use by auxiliary power units was ignored.
- Aircraft weight was calculated for the amount of fuel required for an individual mission plus reserves. For short flights, aircraft often do not refuel at each airport and thus are flying at greater weights than considered here.

Parametric studies are planned to quantify and evaluate the effects of some of these simplifying approximations on the calculated fuel usage and emissions. Work is also planned to calculate explicitly the seasonal variation in fuel usage and emissions for one year of scheduled commercial air traffic.

7.5 Database Availability

An inventory of jet fuel burned and emissions (NOx, CO, total hydrocarbons) has been calculated for 1990 and projected to 2015 for both subsonic aircraft and supersonic aircraft. This data is available on a 1 degree latitude x 1 degree longitude x 1 km altitude grid from either Dr. Robert K. Seals (seals@eosdps.larc.nasa.gov) or Karen H. Sage (sage@uadp2.larc.nasa.gov) at NASA Langley Research Center. The files can be accessed via an anonymous ftp server.

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9. Glossary

AESA	Atmospheric Effects of Stratospheric Aircraft
APU	Auxiliary power unit
ASM	Available seat mile (the number of seats an airline provides times the number of miles they are flown)
ATC	Air traffic control
ATM	Available ton-miles (the number of tons capable of being carried times the number of miles flown)
BCAG	Boeing Commercial Airplane Group
BMAP	Boeing Mission Analysis Process
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EI(CO)	Emission Index (grams CO/kg fuel burn)
EI(HC)	Emission Index [grams hydrocarbon (as CH_4)/kg fuel burn]
EI(NOx)	Emission Index (grams NOx (as NO_2)/kg fuel burn)
FAA	Federal Aviation Administration
GAEC	Global Atmospheric Emissions Code
GE	General Electric
HC	Unburned hydrocarbon
HSCT	High Speed Civil Transport
HSRP	High Speed Research Program (NASA)
ICAO	International Civil Aviation Organization
ISA	International standard atmosphere
kg	kilogram
lb	pound
Load Factor	Percentage of an airplane's seat capacity occupied by passengers
LTO cycle	Landing takeoff cycle
M	Mach number
MDC	McDonnell Douglas Corporation
MTOW	Maximum takeoff weight
NASA	National Aeronautics and Space Administration
nm	Nautical mile
NOx	Oxides of nitrogen (NO + NO_2) in units of gram equivalent NO_2
OAG	Official Airline Guide
OEW	Operating Empty Weight
P&W	Pratt & Whitney

PAX	passengers
RPM	Revenue passenger miles (the number of paying passengers times the number of miles they fly)
RTM	Revenue ton-miles (number of tons carried times the number of miles flown)
TBE	Turbine bypass engine
ton	2000 pounds
3D	Three dimensional

Appendix A. HSCT City Codes

Code	City	Code	City
AKL	AUCKLAND, NEW ZEALAND	MNL	MANILA, PHILIPPINES
AMS	AMSTERDAM, NETHERLAND	MOW	MOSCOW, RUSSIA
ANC	ANCHORAGE, ALASKA	MRU	MAURITIUS, MAURITIUS
ATH	ATHENS, GREECE	MSP	MINNEAPOLIS/ST. PAUL, MN
ATL	ATLANTA, GA	NBO	NAIROBI, KENYA
BAH	BAHRAIN, BAHRAIN	NYC	NEW YORK, NY
BKK	BANGKOK, THAILAND	OSA	OSAKA, JAPAN
BOG	BOGOTA, COLOMBIA	OSL	OSLO, NORWAY
BOM	BOMBAY, INDIA	PAR	PARIS, FRANCE
BOS	BOSTON, MA	PDX	PORTLAND, OR
BRU	BRUSSELS, BELGIUM	PEK	BEIJING, P. R. CHINA
BUD	BUDAPEST, HUNGARY	PER	PERTH, AUSTRALIA
BUE	BUENOS AIRES, ARGENTINA	PHX	PHOENIX, ARIZONA
CAI	CAIRO, EGYPT	PPT	PAPEETE, FRENCH POLYNESIA
CCS	CARACAS, VENEZUELA	RIO	RIO DE JANEIRO, BRAZIL
CHI	CHICAGO, IL	ROM	ROME, ITALY
CPH	COPENHAGEN, DENMARK	SCL	SANTIAGO, CHILE
DFW	DALLAS/FT. WORTH, TX	SEA	SEATTLE/TACOMA, WA
DHA	DHAHRAN, SAUDI ARABIA	SEL	SEOUL, REPUBLIC OF KOREA
DKR	DAKAR, SENEGAL	SFO	SAN FRANCISCO, CA
DTW	DETROIT, MI	SIN	SINGAPORE
FRA	FRANKFURT, GERMANY	SJU	SAN JUAN, PUERTO RICO
GUM	GUAM	SNN	SHANNON, IRELAND
GVA	GENEVA, SWITZERLAND	STL	ST. LOUIS, MO
HEL	HELSINKI, FINLAND	STO	STOCKHOLM, SWEDEN
HKG	HONG KONG	SYD	SYDNEY, NSW, AUSTRALIA
HNL	HONOLULU, HAWAII	TLV	TEL AVIV, ISRAEL
JKT	JAKARTA, INDONESIA	TPE	TAIPEI, TAIWAN
JNB	JOHANNESBURG, SOUTH AFRICA	TYO	TOKYO, JAPAN
LAX	LOS ANGELES, CA	VIE	VIENNA, AUSTRIA
LIM	LIMA, PERU	WAS	WASHINGTON, DC
LIS	LISBON, PORTUGAL	WAW	WARSAW, POLAND
LON	LONDON, UNITED KINGDOM	YMQ	MONTREAL, CANADA
MAD	MADRID, SPAIN	YVR	VANCOUVER, CANADA
MEL	MELBOURNE, AUSTRALIA	YYC	CALGARY, CANADA
MEX	MEXICO CITY, MEXICO	YYZ	TORONTO, CANADA
MIA	MIAMI, FL		

Appendix B. HSCT Flight Frequencies

Emission network city-pairs and daily flight frequencies for year 2015, assuming 500 active HSCTs with seat capacity of 300 and Mach 2.4. The great circle (GC) distances are also shown along with the actual path distances. Waypoint routing locations are listed in Appendix C.

From	Via	To	Flights per day	GC Dist. (nm)	Path Dist. (nm)
AKL	MNL	HKG	2	4937	5022
AKL		HNL	12	3826	3827
AKL	HNL	LAX	9	5659	6044
AKL		PPT	1	2209	2210
AKL		SIN	3	4541	4838
AKL		TYO	5	4768	4769
AMS		ATL	2	3812	4002
AMS		BOS	1	2993	3133
AMS		CCS	1	4230	4232
AMS		CHI	1	3567	3876
AMS		DFW	1	4262	4630
AMS	YYC	LAX	2	4832	5158
AMS		MSP	1	3607	4106
AMS		NYC	5	3155	3248
AMS	BAH	SIN	2	5669	6573
AMS	HEL	TYO	1	5028	5579
AMS		YMQ	1	2972	3349
AMS		YYZ	2	3232	3519
ANC		HKG	1	4397	4947
ANC		LON	1	3885	4011
ANC		PAR	1	4057	4155
ANC		TPE	2	4057	4234
ANC		TYO	8	2975	3045
ATH		NYC	1	4274	4318
ATH	BAH	SIN	1	4885	5654
ATL		AMS	2	3812	4002
ATL		FRA	5	3997	4215
ATL		GVA	1	4005	4147
ATL		LON	5	3648	3807
ATL		PAR	1	3806	3967
BAH		BOM	3	1302	1423
BAH		FRA	3	2395	2721
BAH		GVA	1	2422	2673
BAH		JKT	9	3801	3861
BAH		MNL	1	3976	4672
BAH		SIN	14	3412	3659
BKK		CAI	2	3915	4463
BKK	BAH	CPH	3	4644	6456
BKK		DHA	3	2918	3480
BOG		NYC	1	3847	2168
BOM		BAH	3	1302	1423
BOM		GVA	1	3623	4045
BOM		NBO	1	2446	2505
BOM		PAR	1	3774	4232
BOM		DHA	2	1327	1441
BOS		AMS	1	2993	3133
BOS		FRA	2	3177	3286
BOS		GVA	1	3185	3278
BOS		LON	6	2827	2937
BOS		PAR	1	2985	3101

From	Via	To	Flights per day	GC Dist. (nm)	Path Dist. (nm)
BOS		SNN	2	2506	2608
BRU		CHI	1	3602	3868
BRU		NYC	4	3176	3240
BRU	HEL	TYO	1	5103	5646
BRU		YMQ	1	3000	3115
BUD		NYC	1	3785	3895
BUE	DKR	MAD	2	5441	6098
CAI		BKK	2	3915	4463
CCS		AMS	1	4230	4232
CCS		LIS	1	3508	3509
CCS		MAD	2	3779	3780
CCS		ROM	1	4497	4498
CHI		AMS	1	3567	3876
CHI		BRU	1	3602	3868
CHI		FRA	6	3761	4030
CHI		GVA	2	3806	4014
CHI		LON	6	3423	3681
CHI		PAR	2	3595	3845
CHI		ROM	2	4176	4363
CHI	SEA	TYO	13	5435	5622
CPH	BAH	BKK	3	4644	6456
CPH		LAX	1	4871	4909
CPH		NYC	1	3339	3481
CPH		SEA	1	4214	4346
CPH	HEL	TYO	1	4700	5239

From	Via	To	Flights per day	GC Dist. (nm)	Path Dist. (nm)
DFW		AMS	1	4262	4630
DFW		FRA	2	4455	4784
DFW		LON	6	4115	4435
DFW		PAR	2	4286	4595
DFW	SEA	TYO	3	5569	5572
DHA		BKK	3	2918	3480
DHA		BOM	2	1327	1441
DHA		LON	3	2731	3006
DHA		MNL	7	4001	4690
DHA		PAR	1	2584	2836
DHA		SIN	5	3436	3677
DKR		PAR	6	2280	2494
DTW		FRA	2	3603	3827
DTW		LON	1	3261	3478
DTW		PAR	2	3430	3616
DTW	SEA	SEL	5	5738	6347
DTW	SEA	TYO	5	5542	5801
FRA		ATL	5	3997	4215
FRA		BAH	3	2395	2721
FRA		BOS	2	3177	3286
FRA		CHI	6	3761	4030
FRA		DFW	2	4455	4784
FRA		DTW	2	3603	3827
FRA	YYC	LAX	3	5029	5137
FRA		SFO	1	4936	4953

From	Via	To	Flights per day	GC Dist. (nm)	Path Dist. (nm)
FRA		MIA	4	4188	4238
FRA		NYC	13	3340	3402
FRA	DKR	RIO	2	5163	5606
FRA	BAH	SIN	3	5543	6380
FRA	HEL	TYO	5	5054	5587
FRA		WAS	3	3534	3590
FRA		YMQ	1	3161	3502
FRA		YYC	1	4062	4090
FRA		YYZ	3	3422	3672
GUM		HNL	5	3296	3297
GUM		SIN	1	2533	2534
GUM		SYD	1	2869	3062
GVA		ATL	1	4005	4147
GVA		BAH	1	2422	2673
GVA		BOM	1	3623	4045
GVA		BOS	1	3185	3278
GVA		CHI	2	3806	4014
GVA		NYC	4	3346	3386
GVA		YMQ	1	3191	3258
HEL		NYC	1	3565	3742
HKG	MNL	AKL	2	4937	5022
HKG		ANC	1	4397	4947
HKG	TYO	LAX	7	6282	6590
HKG	TYO	SEA	3	5625	5998
HKG	TYO	SFO	11	5994	6306

From	Via	To	Flights per day	GC Dist. (nm)	Path Dist. (nm)
HKG		SYD	11	3981	4532
HKG	TYO	YVR	8	5533	5919
HNL		AKL	12	3826	3827
HNL		GUM	5	3296	3297
HNL		LAX	31	2216	2217
HNL		MNL	5	4597	4598
HNL		OSA	14	3557	3558
HNL		PHX	1	2528	2529
HNL		PPT	7	2383	2384
HNL		SEA	4	2324	2324
HNL		SEL	7	3950	4602
HNL		SFO	18	2080	2081
HNL		SYD	18	4409	4420
HNL		TPE	4	4394	4395
HNL		TYO	54	3311	3311
HNL		YVR	5	2347	2348
JKT		BAH	9	3801	3861
JKT		TYO	5	3145	3288
JNB		RIO	1	3859	3859
LAX	HNL	AKL	9	5659	6044
LAX	YYC	AMS	2	4832	5158
LAX		CPH	1	4871	4909
LAX	YYC	FRA	3	5029	5137
LAX	TYO	HKG	7	6282	6590
LAX		HNL	31	2216	2217

From	Via	To	Flights per day	GC Dist. (nm)	Path Dist. (nm)
LAX		LON	7	4726	4870
LAX	HNL	MEL	4	6884	7017
LAX		OSA	3	4955	4956
LAX	YYC	PAR	2	4910	5189
LAX	TYO	PEK	1	5415	5876
LAX		PPT	3	3567	3568
LAX	LIM	RIO	1	5470	5757
LAX	NYC	ROM	1	5504	5884
LAX	HNL	SYD	7	6508	6637
LAX	TYO	TPE	8	5893	5912
LAX		TYO	35	4723	4724
LIM		MIA	3	2276	2402
LIS		CCS	1	3508	3509
LIS		NYC	2	2916	2917
LIS		RIO	2	4163	4337
LON		ANC	1	3885	4011
LON		ATL	5	3648	3807
LON		BOS	6	2827	2937
LON		CHI	6	3423	3681
LON		DFW	6	4115	4435
LON		DHA	3	2731	3006
LON		DTW	1	3261	3478
LON		LAX	7	4726	4870
LON		MIA	7	3835	3842
LON		MSP	1	3476	3910

From	Via	To	Flights per day	GC Dist. (nm)	Path Dist. (nm)
LON		NYC	27	2990	3053
LON	DKR	RIO	2	4993	5347
LON		SEA	1	4156	4307
LON		SFO	3	4649	4778
LON	BAH	SIN	8	5868	6689
LON		SJU	4	3633	3634
LON		STL	1	3638	3825
LON	HEL	TYO	11	5175	5754
LON		WAS	6	3184	3241
LON		YMQ	2	2817	3153
LON		YVR	1	4090	4286
LON		YYC	1	3786	3916
LON		YYZ	7	3079	3323
MAD	DKR	BUE	2	5441	6098
MAD		CCS	2	3779	3780
MAD		MEX	2	4892	4893
MAD		MIA	2	3834	3835
MAD		NYC	5	3109	3124
MAD		RIO	3	4395	4591
MAD		SJU	2	3444	3443
MEL	HNL	LAX	4	6884	7017
MEX		MAD	2	4892	4893
MIA		FRA	4	4188	4238
MIA		LIM	3	2276	2402
MIA		LON	7	3835	3842

From	Via	To	Flights per day	GC Dist. (nm)	Path Dist. (nm)
MIA		MAD	2	3834	3835
MIA		PAR	2	3976	3989
MIA		SCL	2	3592	3690
MNL		BAH	1	3976	4672
MNL		DHA	7	4001	4690
MNL		HNL	5	4597	4598
MNL		SYD	3	3380	3920
MOW		NYC	2	4037	4208
MRU		SIN	1	3013	3014
MRU		TPE	1	4602	4698
MSP		AMS	1	3607	4106
MSP		LON	1	3476	3910
MSP	SEA	TYO	2	5154	5343
NBO		BOM	1	2446	2505
NYC		AMS	5	3155	3248
NYC		ATH	1	4274	4318
NYC		BOG	1	3847	2168
NYC		BRU	4	3176	3240
NYC		BUD	1	3785	3895
NYC		CPH	1	3339	3481
NYC		FRA	13	3340	3402
NYC		GVA	4	3346	3386
NYC		HEL	1	3565	3742
NYC		LIS	2	2916	2917
NYC		LON	27	2990	3053

From	Via	To	Flights per day	GC Dist. (nm)	Path Dist. (nm)
NYC		MAD	5	3109	3124
NYC		MOW	2	4037	4208
NYC		OSL	1	3192	3341
NYC		PAR	12	3148	3216
NYC		ROM	10	3704	3740
NYC	SEA	SEL	5	5974	6775
NYC		SNN	2	2669	2723
NYC		STO	1	3395	3549
NYC	ROM	TLV	2	4920	5200
NYC	SEA	TYO	21	5844	6229
NYC		WAW	1	3695	3786
OSA		HNL	14	3557	3558
OSA		LAX	3	4955	4956
OSA		SIN	7	2668	2843
OSL		NYC	1	3192	3341
PAR		ANC	1	4057	4155
PAR		ATL	1	3806	3967
PAR		BOM	1	3774	4232
PAR		BOS	1	2985	3101
PAR		CHI	2	3595	3845
PAR		DFW	2	4286	4595
PAR		DHA	1	2584	2836
PAR		DKR	6	2280	2494
PAR		DTW	2	3430	3616
PAR	YYC	LAX	2	4910	5189

From	Via	To	Flights per day	GC Dist. (nm)	Path Dist. (nm)
PAR		MIA	2	3976	3989
PAR		NYC	12	3148	3216
PAR	DKR	RIO	2	4956	5311
PAR		SJU	8	3734	3725
PAR	BAH	SIN	1	5783	6519
PAR	HEL	TYO	5	5239	5798
PAR		WAS	3	3343	3405
PAR		YMQ	6	2984	3317
PAR		YYZ	1	3248	3461
PDX		SEL	3	4566	4728
PDX		TYO	3	4177	4178
PEK	TYO	LAX	1	5415	5876
PER		TYO	3	4287	4288
PHX		HNL	1	2528	2529
PPT		AKL	1	2209	2210
PPT		HNL	7	2383	2384
PPT		LAX	3	3567	3568
PPT		SFO	1	3649	3650
PPT		SYD	1	3301	3302
PPT	GUM	TYO	2	5096	5665
RIO	DKR	FRA	2	5163	5606
RIO		JNB	1	3859	3859
RIO	LIM	LAX	1	5470	5757
RIO		LIS	2	4163	4337
RIO	DKR	LON	2	4993	5347

From	Via	To	Flights per day	GC Dist. (nm)	Path Dist. (nm)
RIO		MAD	3	4395	4591
RIO	DKR	PAR	2	4956	5311
RIO	DKR	ROM	2	4949	5771
ROM		CCS	1	4497	4498
ROM		CHI	2	4176	4363
ROM	NYC	LAX	1	5504	5884
ROM		NYC	10	3704	3740
ROM	DKR	RIO	2	4949	5771
ROM	HEL	TYO	1	5343	5962
ROM		YYZ	1	3823	4031
SCL		MIA	2	3592	3690
SEA		CPH	1	4214	4346
SEA	TYO	HKG	3	5625	5998
SEA		HNL	4	2324	2324
SEA		LON	1	4156	4307
SEA		SEL	1	4503	4678
SEA	TYO	TPE	1	5264	5320
SEA		TYO	9	4131	4132
SEL	SEA	DTW	5	5738	6347
SEL		HNL	7	3950	4602
SEL	SEA	NYC	5	5974	6775
SEL		PDX	3	4566	4728
SEL		SEA	1	4503	4678
SEL		SIN	1	2511	2573
SEL		YVR	2	4411	4455

From	Via	To	Flights per day	GC Dist. (nm)	Path Dist. (nm)
SFO		FRA	1	4936	4953
SFO	TYO	HKG	11	5994	6306
SFO		HNL	18	2080	2081
SFO		LON	3	4649	4778
SFO		PPT	1	3649	3650
SFO	HNL	SYD	2	6448	6501
SFO	TYO	TPE	5	5607	5628
SFO		TYO	29	4439	4440
SIN		AKL	3	4541	4838
SIN	BAH	AMS	2	5669	6573
SIN	BAH	ATH	1	4885	5654
SIN		BAH	14	3412	3659
SIN		DHA	5	3436	3677
SIN	BAH	FRA	3	5543	6380
SIN		GUM	1	2533	2534
SIN	BAH	LON	8	5868	6689
SIN		MRU	1	3013	3014
SIN		OSA	7	2668	2843
SIN	BAH	PAR	1	5783	6519
SIN		SEL	1	2511	2573
SIN		TLV	1	4293	4641
SIN		TPE	2	1740	1742
SIN		TYO	32	2893	2947
SIN	BAH	VIE	1	5232	6302
SJU		LON	4	3633	3634

From	Via	To	Flights per day	GC Dist. (nm)	Path Dist. (nm)
SJU		MAD	2	3444	3443
SJU		PAR	8	3734	3725
SNN		BOS	2	2506	2608
SNN		NYC	2	2669	2723
STL		LON	1	3638	3825
STO		NYC	1	3395	3549
SYD		GUM	1	2869	3062
SYD		HKG	11	3981	4532
SYD		HNL	18	4409	4420
SYD	HNL	LAX	7	6508	6637
SYD		MNL	3	3380	3920
SYD		PPT	1	3301	3302
SYD	HNL	SFO	2	6448	6501
SYD		TYO	20	4226	4385
TLV	ROM	NYC	2	4920	5200
TLV		SIN	1	4293	4641
TPE		ANC	2	4057	4234
TPE		HNL	4	4394	4395
TPE	TYO	LAX	8	5893	5912
TPE		MRU	1	4602	4698
TPE	TYO	SEA	1	5264	5320
TPE	TYO	SFO	5	5607	5628
TPE		SIN	2	1740	1742
TPE	TYO	YVR	1	5176	5241
TYO		AKL	5	4768	4769

From	Via	To	Flights per day	GC Dist. (nm)	Path Dist. (nm)
TYO	HEL	AMS	1	5028	5579
TYO		ANC	8	2975	3045
TYO	HEL	BRU	1	5103	5646
TYO	SEA	CHI	13	5435	5622
TYO	HEL	CPH	1	4700	5239
TYO	SEA	DFW	3	5569	5572
TYO	SEA	DTW	5	5542	5801
TYO	HEL	FRA	5	5054	5587
TYO		HNL	54	3311	3311
TYO		JKT	5	3145	3288
TYO		LAX	35	4723	4724
TYO	HEL	LON	11	5175	5754
TYO	SEA	MSP	2	5154	5343
TYO	SEA	NYC	21	5844	6229
TYO	HEL	PAR	5	5239	5798
TYO		PDX	3	4177	4178
TYO		PER	3	4287	4288
TYO	GUM	PPT	2	5096	5665
TYO	HEL	ROM	1	5343	5962
TYO		SEA	9	4131	4132
TYO		SFO	29	4439	4440
TYO		SIN	32	2893	2947
TYO		SYD	20	4226	4385
TYO	SEA	WAS	6	5851	6129
TYO		YVR	9	4050	4053
TYO	YVR	YYZ	2	5557	5858
VIE	BAH	SIN	1	5232	6302
WAS		FRA	3	3534	3590
WAS		LON	6	3184	3241
WAS		PAR	3	3343	3405
WAS	SEA	TYO	6	5851	6129
WAW		NYC	1	3695	3786
YMQ		AMS	1	2972	3349
YMQ		BRU	1	3000	3115
YMQ		FRA	1	3161	3502
YMQ		GVA	1	3191	3258
YMQ		LON	2	2817	3153
YMQ		PAR	6	2984	3317
YVR	TYO	HKG	8	5533	5919
YVR		HNL	5	2347	2348
YVR		LON	1	4090	4286
YVR		SEL	2	4411	4455
YVR	TYO	TPE	1	5176	5241
YVR		TYO	9	4050	4053
YYC		FRA	1	4062	4090
YYC		LON	1	3786	3916
YYZ		AMS	2	3232	3519
YYZ		FRA	3	3422	3672
YYZ		LON	7	3079	3323
YYZ		PAR	1	3248	3461
YYZ		ROM	1	3823	4031
YYZ	YVR	TYO	2	5557	5858

Appendix C. HSCT Routing Table

The following table provides a list of the number of departures flown between each city pair. It also includes the waypoints (latitude, longitude) used to avoid supersonic flight over land. Great circle routes were flown between city pairs unless waypoint routing was necessary. If waypoints were used, great circle routes were flown between the waypoints.

Flights per week	From	To	Waypoints to Avoid Flying Supersonically over Land											
140	AKL	HNL												
14	AKL	MNL	1000S	15200E	0330S	14700E								
7	AKL	PPT												
21	AKL	SIN	2000S	15500E	1000S	14200E	0700S	12000E	0307S	10900E				
35	AKL	TYO												
14	AMS	ATL	5100N	00900W	3226N	07823W								
14	AMS	BAH	4530N	01221E	4000N	01900E	3720N	01947E	3425N	02400E	3110N	03325E	2845N	03440E
7	AMS	BOS	5100N	00900W	4700N	05000W	4108N	06700W						
7	AMS	CCS	5100N	00900W										
7	AMS	CHI	5100N	00900W	4700N	05000W	4108N	06700W						
7	AMS	DFW	5100N	00900W	3226N	07823W								
7	AMS	HEL												
7	AMS	MSP	5100N	00900W	4700N	05000W	4108N	06700W						
35	AMS	NYC	5100N	00900W	4700N	05000W	4108N	06700W						
7	AMS	YMQ	5100N	00900W	4700N	05000W	4108N	06700W						
7	AMS	YYC	6000N	00500W	5800N	04500W	6100N	06500W	6200N	07000W	6300N	07500W	6230N	08000W
14	AMS	YYZ	5100N	00900W	4700N	05000W	4108N	06700W						
7	ANC	HKG	5730N	16500W	4600N	14800E	3500N	14200E	2000N	12500E				
7	ANC	LON	8500N	01000W	6230N	00300E	5700N	00300E						
7	ANC	PAR	8500N	01000W	6230N	00300E	5700N	00300E						
14	ANC	TPE	5730N	16500W	3330N	14000E								
49	ANC	TYO	5730N	16500W	4600N	14800E								
7	ATH	BAH	3720N	01947E	3425N	02400E	3110N	03325E	2845N	03440E				
7	ATH	NYC	4450N	00043W	4600N	00800W	4600N	05000W	4108N	06700W				
14	ATL	AMS	3226N	07823W	5100N	00900W								
35	ATL	FRA	3226N	07823W	4800N	00600W								
7	ATL	GVA	3226N	07823W	4700N	05000W	5100N	00900W						
35	ATL	LON	3226N	07823W	5100N	00900W								
7	ATL	PAR	3226N	07823W	4800N	00600W								
14	BAH	AMS	2845N	03440E	3110N	03325E	3425N	02400E	3720N	01947E	4000N	01900E	4530N	01221E

Flights per week	From	To	Waypoints to Avoid Flying Supersonically over Land													
7	BAH	ATH	2845N	03440E	3110N	03325E	3425N	02400E	3720N	01947E						
21	BAH	BKK	1930N	05740E	0500N	08000E										
21	BAH	BOM	1930N	05740E												
21	BAH	CPH	2845N	03440E	3110N	03325E	3425N	02400E	4000N	01900E	4530N	01221E				
42	BAH	FRA	2845N	03440E	3110N	03325E	3425N	02400E	3720N	01947E	4000N	01900E	4530N	01221E		
7	BAH	GVA	2845N	03440E	3110N	03325E	3425N	02400E	3720N	01947E	4000N	01900E	4530N	01221E		
63	BAH	JKT	1930N	05740E	0500N	08000E										
56	BAH	LON	2845N	03440E	3110N	03325E	3425N	02400E	3720N	01947E	4000N	01900E	4530N	01221E		
7	BAH	MNL	1930N	05740E	0500N	08000E	0610N	09700E	0800N	10800E						
7	BAH	PAR	2845N	03440E	3110N	03325E	3425N	02400E	3720N	01947E	4000N	01900E	4530N	01221E		
203	BAH	SIN	1930N	05740E	0500N	08000E	0610N	09700E	0200N	10200E						
7	BAH	VIE	2845N	03440E	3110N	03325E	3425N	02400E	3720N	01947E	4000N	01900E	4530N	01221E		
21	BKK	BAH	0500N	08000E	1930N	05740E										
14	BKK	CAI	0500N	08000E	1930N	05740E	2845N	03440E								
21	BKK	DHA	0500N	08000E	1930N	05740E										
7	BOG	NYC	2600N	07600W												
21	BOM	BAH	1930N	05740E												
14	BOM	DHA	1930N	05740E												
7	BOM	GVA	1930N	05740E	2845N	03440E	3110N	03325E	3425N	02400E	3720N	01947E	4000N	01900E	4530N	01221E
7	BOM	NBO	0030S	04500E												
7	BOM	PAR	1930N	05740E	2845N	03440E	3110N	03325E	3425N	02400E	3720N	01947E	4000N	01900E	4530N	01221E
7	BOS	AMS	4108N	06700W	4700N	05000W	5100N	00900W								
14	BOS	FRA	4108N	06700W	4700N	05000W	5100N	00900W								
7	BOS	GVA	4108N	06700W	4700N	05000W	5100N	00900W								
42	BOS	LON	4108N	06700W	4700N	05000W	5100N	00900W								
7	BOS	PAR	4108N	06700W	4800N	00600W										
7	BOS	SNN	4108N	06700W	4700N	05000W										
7	BRU	CHI	5100N	00900W	4700N	05000W	4108N	06700W								
7	BRU	HEL														
28	BRU	NYC	5100N	00900W	4700N	05000W	4108N	06700W								

Flights per week	From	To	Waypoints to Avoid Flying Supersonically over Land											
7	BRU	YMQ	5100N	00900W	4700N	05000W								
7	BUD	NYC	4800N	00600W	4108N	06700W								
14	BUE	DKR	3600S	05200W	2000S	03500W								
14	CAI	BKK	2845N	03440E	1930N	05740E	0500N	08000E						
7	CCS	AMS	5100N	00900W										
7	CCS	LIS												
14	CCS	MAD												
7	CCS	ROM												
7	CHI	AMS	4108N	06700W	4700N	05000W	5100N	00900W						
7	CHI	BRU	4108N	06700W	4700N	05000W	5100N	00900W						
35	CHI	FRA	4108N	06700W	4700N	05000W	5100N	00900W						
14	CHI	GVA	4108N	06700W	4800N	00600W								
42	CHI	LON	4108N	06700W	4700N	05000W	5100N	00900W						
14	CHI	PAR	4108N	06700W	4800N	00600W								
14	CHI	ROM	4108N	06700W										
91	CHI	SEA												
21	CPH	BAH	4530N	01221E	4000N	01900E	3425N	02400E	3110N	03325E	2845N	03440E		
7	CPH	HEL												
7	CPH	NYC	6000N	00500W	4700N	05000W	4108N	06700W						
7	DFW	AMS	3226N	07823W	5100N	00900W								
14	DFW	FRA	3226N	07823W	5100N	00900W								
42	DFW	LON	3226N	07823W	5100N	00900W								
14	DFW	PAR	3226N	07823W	4800N	00600W								
21	DFW	SEA												
21	DHA	BKK	1930N	05740E	0500N	08000E								
14	DHA	BOM	1930N	05740E										
21	DHA	LON	2845N	03440E	3110N	03325E	3425N	02400E	3720N	01947E	4000N	01900E	4530N	01221E
49	DHA	MNL	1930N	05740E	0500N	08000E	0610N	09700E	0800N	10800E				
7	DHA	PAR	2845N	03440E	3110N	03325E	3425N	02400E	3720N	01947E	4000N	01900E	4530N	01221E
35	DHA	SIN	1930N	05740E	0500N	08000E	0610N	09700E	0200N	10200E				

Flights per week	From	To	Waypoints to Avoid Flying Supersonically over Land											
14	DKR	BUE	2000S	03500W	3600S	05200W								
14	DKR	FRA	2000N	02000W	4000N	01700W								
14	DKR	LON	2000N	02000W	4000N	01700W								
14	DKR	MAD	4000N	01700W										
49	DKR	PAR	4000N	01700W										
56	DKR	RIO	2000S	03500W										
14	DKR	ROM	4000N	01700W	3701N	00756W								
14	DTW	FRA	4108N	06700W	4700N	05000W	5100N	00900W						
7	DTW	LON	4108N	06700W	4700N	05000W	5100N	00900W						
14	DTW	PAR	4108N	06700W	4700N	05000W	5100N	00900W						
70	DTW	SEA												
35	FRA	ATL	4800N	00600W	3226N	07823W								
42	FRA	BAH	4530N	01221E	4000N	01900E	3720N	01947E	3425N	02400E	3110N	03325E	2845N	03440E
14	FRA	BOS	5100N	00900W	4700N	05000W	4108N	06700W						
35	FRA	CHI	5100N	00900W	4700N	05000W	4108N	06700W						
14	FRA	DFW	5100N	00900W	3226N	07823W								
14	FRA	DKR	4000N	01700W	2000N	02000W								
14	FRA	DTW	5100N	00900W	4700N	05000W	4108N	06700W						
35	FRA	HEL												
28	FRA	MIA	4800N	00600W										
91	FRA	NYC	5100N	00900W	4700N	05000W	4108N	06700W						
21	FRA	WAS	5100N	00900W	4700N	05000W	4108N	06700W						
7	FRA	YMQ	5100N	00900W	4700N	05000W	4108N	06700W						
35	FRA	YYC	6000N	00500W	5800N	04500W	6100N	06500W	6200N	07000W	6300N	07500W	6230N	08000W
21	FRA	YYZ	5100N	00900W	4700N	05000W	4108N	06700W						
35	GUM	HNL												
14	GUM	PPT												
7	GUM	SIN	0500N	12600E	0600N	12200E	0730N	11700E						
7	GUM	SYD	0330S	14700E	1000S	15200E	2000S	15500E	2500S	15500E	3230S	15400E		
14	GUM	TYO												

Flights per week	From	To	Waypoints to Avoid Flying Supersonically over Land													
7	GVA	ATL	5100N	00900W	4700N	05000W	3226N	07823W								
7	GVA	BAH	4530N	01221E	4000N	01900E	3720N	01947E	3425N	02400E	3110N	03325E	2845N	03440E		
7	GVA	BOM	4530N	01221E	4000N	01900E	3720N	01947E	3425N	02400E	3110N	03325E	2845N	03440E	1930N	05740E
7	GVA	BOS	5100N	00900W	4700N	05000W	4108N	06700W								
14	GVA	CHI	4800N	00600W	4108N	06700W										
28	GVA	NYC	4800N	00600W	4108N	06700W										
7	GVA	YMQ	4700N	05000W												
7	HEL	AMS														
7	HEL	BRU														
7	HEL	CPH														
35	HEL	FRA														
70	HEL	LON														
7	HEL	NYC	4700N	05000W	4108N	06700W										
35	HEL	PAR														
7	HEL	ROM														
168	HEL	TYO	7200N	02500E	7200N	13230E	5910N	14300E	4600N	14800E						
7	HKG	ANC	2000N	12500E	3500N	14200E	4600N	14800E	5730N	16500W						
14	HKG	MNL														
77	HKG	SYD	2000N	12200E	0330S	14700E	1000S	15200E	2000S	15500E	2500S	15500E	3230S	15400E		
203	HKG	TYO	2000N	12500E												
140	HNL	AKL														
35	HNL	GUM														
350	HNL	LAX														
28	HNL	MEL	2500S	16500E												
35	HNL	MNL														
98	HNL	OSA														
7	HNL	PHX														
49	HNL	PPT														
28	HNL	SEA														
49	HNL	SEL	3000N	12500E	3500N	12500E										

Flights per week	From	To	Waypoints to Avoid Flying Supersonically over Land											
133	HNL	SFO												
189	HNL	SYD	2500S	16500E										
28	HNL	TPE												
371	HNL	TYO												
35	HNL	YVR												
63	JKT	BAH	0500N	08000E	1930N	05740E								
35	JKT	TYO	0800N	10800E	3300N	13700E								
7	JNB	RIO												
350	LAX	HNL												
7	LAX	LIM	3000N	11800W	2500N	11500W	1500N	10500W						
49	LAX	LON	6230N	08000W	6300N	07500W	6200N	07000W	6100N	06500W	5800N	04500W	5100N	00900W
7	LAX	NYC												
21	LAX	OSA												
21	LAX	PPT												
357	LAX	TYO												
42	LAX	YYC												
7	LIM	LAX	1500N	10500W	2500N	11500W	3000N	11800W						
21	LIM	MIA	0500S	08300W										
7	LIM	RIO												
7	LIS	CCS												
14	LIS	NYC												
14	LIS	RIO	3000N	01800W	0730S	03200W	2000S	03500W						
7	LON	ANC	5700N	00300E	6230N	00300E	8500N	01000W						
35	LON	ATL	5100N	00900W	3226N	07823W								
56	LON	BAH	4530N	01221E	4000N	01900E	3720N	01947E	3425N	02400E	3110N	03325E	2845N	03440E
42	LON	BOS	5100N	00900W	4700N	05000W	4108N	06700W						
42	LON	CHI	5100N	00900W	4700N	05000W	4108N	06700W						
42	LON	DFW	5100N	00900W	3226N	07823W								
21	LON	DHA	4530N	01221E	4000N	01900E	3720N	01947E	3425N	02400E	3110N	03325E	2845N	03440E
14	LON	DKR	4000N	01700W	2000N	02000W								

Flights per week	From	To	Waypoints to Avoid Flying Supersonically over Land											
7	LON	DTW	5100N	00900W	4700N	05000W	4108N	06700W						
70	LON	HEL												
49	LON	LAX	5100N	00900W	5800N	04500W	6100N	06500W	6200N	07000W	6300N	07500W	6230N	08000W
49	LON	MIA	5100N	00900W										
7	LON	MSP	5100N	00900W	4700N	05000W	4108N	06700W						
182	LON	NYC	5100N	00900W	4700N	05000W	4108N	06700W						
7	LON	SEA	5100N	00900W	5800N	04500W	6100N	06500W	6200N	07000W	6300N	07500W	6230N	08000W
21	LON	SFO	5100N	00900W	5800N	04500W	6100N	06500W	6200N	07000W	6300N	07500W	6230N	08000W
28	LON	SJU	5100N	00900W										
7	LON	STL	5100N	00900W	4700N	05000W	4108N	06700W						
42	LON	WAS	5100N	00900W	4700N	05000W	4108N	06700W						
14	LON	YMQ	5100N	00900W	4700N	05000W	4108N	06700W						
7	LON	YVR	5100N	00900W	5800N	04500W	6100N	06500W	6200N	07000W	6300N	07500W	6230N	08000W
7	LON	YYC	5100N	00900W	5800N	04500W	6100N	06500W	6200N	07000W	6300N	07500W	6230N	08000W
49	LON	YYZ	5100N	00900W	4700N	05000W	4108N	06700W						
14	MAD	CCS												
14	MAD	DKR	4000N	01700W										
14	MAD	MEX												
14	MAD	MIA												
35	MAD	NYC	4108N	06700W										
21	MAD	RIO	3701N	00756W	2700N	02000W	2000S	03500W						
14	MAD	SJU												
28	MEL	HNL	2500S	16500E										
14	MEX	MAD												
28	MIA	FRA	4800N	00600W										
21	MIA	LIM	0500S	08300W										
49	MIA	LON	5100N	00900W										
14	MIA	MAD												
14	MIA	PAR	4800N	00600W										
14	MIA	SCL	0500S	08300W										

Flights per week	From	To	Waypoints to Avoid Flying Supersonically over Land									
14	MNL	AKL	0330S	14700E	1000S	15200E						
7	MNL	BAH	0800N	10800E	0610N	09700E	0500N	08000E	1930N	05740E		
49	MNL	DHA	0800N	10800E	0610N	09700E	0500N	08000E	1930N	05740E		
14	MNL	HKG										
35	MNL	HNL										
21	MNL	SYD	0330S	14700E	1000S	15200E	2000S	15500E	2500S	15500E	3230S	15400E
14	MOW	NYC	6000N	00500W	4700N	05000W	4108N	06700W				
7	MRU	SIN										
7	MRU	TPE	0800N	10800E								
7	MSP	AMS	4108N	06700W	4700N	05000W	5100N	00900W				
7	MSP	LON	4108N	06700W	4700N	05000W	5100N	00900W				
14	MSP	SEA										
7	NBO	BOM	0030S	04500E								
35	NYC	AMS	4108N	06700W	4700N	05000W	5100N	00900W				
7	NYC	ATH	4108N	06700W	4600N	05000W	4600N	00800W	4450N	00043W		
7	NYC	BOG	2600N	07600W								
28	NYC	BRU	4108N	06700W	4700N	05000W	5100N	00900W				
7	NYC	BUD	4108N	06700W	4800N	00600W						
7	NYC	CPH	4108N	06700W	4700N	05000W	6000N	00500W				
91	NYC	FRA	4108N	06700W	4700N	05000W	5100N	00900W				
28	NYC	GVA	4108N	06700W	4800N	00600W						
7	NYC	HEL	4108N	06700W	4700N	05000W						
7	NYC	LAX										
14	NYC	LIS										
182	NYC	LON	4108N	06700W	4700N	05000W	5100N	00900W				
35	NYC	MAD	4108N	06700W								
14	NYC	MOW	4108N	06700W	4700N	05000W	6000N	00500W				
7	NYC	OSL	4108N	06700W	4700N	05000W						
77	NYC	PAR	4108N	06700W	4800N	00600W						
91	NYC	ROM	4108N	06700W	4600N	00800W						

Flights per week	From	To	Waypoints to Avoid Flying Supersonically over Land													
175	NYC	SEA														
14	NYC	SNN	4108N	06700W	4700N	05000W										
7	NYC	STO	4108N	06700W	4700N	05000W										
7	NYC	WAW	4108N	06700W	4700N	05000W										
98	OSA	HNL														
21	OSA	LAX														
49	OSA	SIN	3300N	13700E	0700N	10500E										
7	OSL	NYC	4700N	05000W	4108N	06700W										
7	PAR	ANC	5700N	00300E	6230N	00300E	8500N	01000W								
7	PAR	ATL	4800N	00600W	3226N	07823W										
7	PAR	BAH	4530N	01221E	4000N	01900E	3720N	01947E	3425N	02400E	3110N	03325E	2845N	03440E		
7	PAR	BOM	4530N	01221E	4000N	01900E	3720N	01947E	3425N	02400E	3110N	03325E	2845N	03440E	1930N	05740E
7	PAR	BOS	4800N	00600W	4108N	06700W										
14	PAR	CHI	4800N	00600W	4108N	06700W										
14	PAR	DFW	4800N	00600W	3226N	07823W										
7	PAR	DHA	4530N	01221E	4000N	01900E	3720N	01947E	3425N	02400E	3110N	03325E	2845N	03440E		
49	PAR	DKR	4000N	01700W												
14	PAR	DTW	5100N	00900W	4700N	05000W	4108N	06700W								
35	PAR	HEL														
14	PAR	MIA	4800N	00600W												
77	PAR	NYC	4800N	00600W	4108N	06700W										
56	PAR	SJU	4800N	00600W												
21	PAR	WAS	4800N	00600W	4108N	06700W										
42	PAR	YMQ	4800N	00600W	4108N	06700W										
14	PAR	YYC	4800N	00600W	5800N	04500W	6100N	06500W	6200N	07000W	6300N	07500W	6230N	08000W		
7	PAR	YYZ	5100N	00900W	4700N	05000W	4108N	06700W								
21	PDX	SEL	5000N	17900W	3816N	14052E										
21	PDX	TYO														
7	PEK	TYO														
21	PER	TYO														

Flights per week	From	To	Waypoints to Avoid Flying Supersonically over Land											
7	PHX	HNL												
7	PPT	AKL												
14	PPT	GUM												
49	PPT	HNL												
21	PPT	LAX												
7	PPT	SFO												
7	PPT	SYD												
56	RIO	DKR	2000S	03500W										
7	RIO	JNB												
7	RIO	LIM												
14	RIO	LIS	2000S	03500W	0730S	03200W	3000N	01800W						
21	RIO	MAD	2000S	03500W	2700N	02000W	3701N	00756W						
7	ROM	CCS												
14	ROM	CHI	4108N	06700W										
14	ROM	DKR	3701N	00756W	4000N	01700W								
7	ROM	HEL												
91	ROM	NYC	4600N	00800W	4108N	06700W								
14	ROM	TLV	3700N	01200E	3425N	02400E								
7	ROM	YYZ	5100N	00900W	4108N	06700W								
14	SCL	MIA	0500S	08300W										
91	SEA	CHI												
21	SEA	DFW												
70	SEA	DTW												
28	SEA	HNL												
7	SEA	LON	6230N	08000W	6300N	07500W	6200N	07000W	6100N	06500W	5800N	04500W	5100N	00900W
14	SEA	MSP												
175	SEA	NYC												
77	SEA	SEL	5000N	17900W	3816N	14052E								
434	SEA	TYO	5000N	17900W										
42	SEA	WAS												

Flights per week	From	To	Waypoints to Avoid Flying Supersonically over Land											
49	SEL	HNL	3500N	12500E	3000N	12500E								
21	SEL	PDX	3816N	14052E	5000N	17900W								
77	SEL	SEA	3816N	14052E	5000N	17900W								
7	SEL	SIN	3500N	12500E	3000N	12500E	0800N	10800E						
14	SEL	YVR	3816N	14052E	5000N	17900W								
133	SFO	HNL												
21	SFO	LON	6230N	08000W	6300N	07500W	6200N	07000W	6100N	06500W	5800N	04500W	5100N	00900W
7	SFO	PPT												
308	SFO	TYO												
7	SFO	YYC												
21	SIN	AKL	0307S	10900E	0700S	12000E	1000S	14200E	2000S	15500E				
203	SIN	BAH	0200N	10200E	0610N	09700E	0500N	08000E	1930N	05740E				
35	SIN	DHA	0200N	10200E	0610N	09700E	0500N	08000E	1930N	05740E				
7	SIN	GUM	0730N	11700E	0600N	12200E	0500N	12600E						
7	SIN	MRU												
49	SIN	OSA	0700N	10500E	3300N	13700E								
7	SIN	SEL	0800N	10800E	3000N	12500E	3500N	12500E						
7	SIN	TLV	0500N	08000E	1930N	05740E	2845N	03440E	3110N	03325E				
14	SIN	TPE	0800N	10800E										
224	SIN	TYO	0700N	10500E	3300N	13700E								
28	SJU	LON	5100N	00900W										
14	SJU	MAD												
56	SJU	PAR	4800N	00600W										
7	SNN	BOS	4700N	05000W	4108N	06700W								
14	SNN	NYC	4700N	05000W	4108N	06700W								
7	STL	LON	4108N	06700W	4700N	05000W	5100N	00900W						
7	STO	NYC	4700N	05000W	4108N	06700W								
7	SYD	GUM	3230S	15400E	2500S	15500E	2000S	15500E	1000S	15200E	0330S	14700E		
77	SYD	HKG	3230S	15400E	2500S	15500E	2000S	15500E	1000S	15200E	0330S	14700E	2000N	12200E
189	SYD	HNL	2500S	16500E										

Flights per week	From	To	Waypoints to Avoid Flying Supersonically over Land											
21	SYD	MNL	3230S	15400E	2500S	15500E	2000S	15500E	1000S	15200E	0330S	14700E		
7	SYD	PPT												
140	SYD	TYO	3230S	15400E	2500S	15500E	2000S	15500E	0500S	15400E				
14	TLV	ROM	3425N	02400E	3700N	01200E								
7	TLV	SIN	3110N	03325E	2845N	03440E	1930N	05740E	0500N	08000E				
14	TPE	ANC	3330N	14000E	5730N	16500W								
28	TPE	HNL												
7	TPE	MRU	0800N	10800E										
14	TPE	SIN	0800N	10800E										
105	TPE	TYO	3300N	13700E										
35	TYO	AKL												
49	TYO	ANC	4600N	14800E	5730N	16500W								
14	TYO	GUM												
168	TYO	HEL	4600N	14800E	5910N	14300E	7200N	13230E	7200N	02500E				
203	TYO	HKG	2000N	12500E										
371	TYO	HNL												
35	TYO	JKT	3300N	13700E	0800N	10800E								
357	TYO	LAX												
21	TYO	PDX												
7	TYO	PEK												
21	TYO	PER												
434	TYO	SEA	5000N	17900W										
308	TYO	SFO												
224	TYO	SIN	3300N	13700E	0700N	10500E								
140	TYO	SYD	0500S	15400E	2000S	15500E	2500S	15500E	3230S	15400E				
105	TYO	TPE	3300N	13700E										
133	TYO	YVR	5000N	17900W										
7	VIE	BAH	4530N	01221E	4000N	01900E	3720N	01947E	3425N	02400E	3110N	03325E	2845N	03440E
21	WAS	FRA	4108N	06700W	4700N	05000W	5100N	00900W						
42	WAS	LON	4108N	06700W	4700N	05000W	5100N	00900W						

Flights per week	From	To	Waypoints to Avoid Flying Supersonically over Land											
21	WAS	PAR	4108N	06700W	4800N	00600W								
42	WAS	SEA												
7	WAW	NYC	4700N	05000W	4108N	06700W								
7	YMQ	AMS	4108N	06700W	4700N	05000W	5100N	00900W						
7	YMQ	BRU	4700N	05000W	5100N	00900W								
7	YMQ	FRA	4108N	06700W	4700N	05000W	5100N	00900W						
7	YMQ	GVA	4700N	05000W										
14	YMQ	LON	4108N	06700W	4700N	05000W	5100N	00900W						
42	YMQ	PAR	4108N	06700W	4800N	00600W								
35	YVR	HNL												
7	YVR	LON	6230N	08000W	6300N	07500W	6200N	07000W	6100N	06500W	5800N	04500W	5100N	00900W
14	YVR	SEL	5000N	17900W	3816N	14052E								
133	YVR	TYO	5000N	17900W										
14	YVR	YYZ												
7	YYC	AMS	6230N	08000W	6300N	07500W	6200N	07000W	6100N	06500W	5800N	04500W	6000N	00500W
35	YYC	FRA	6230N	08000W	6300N	07500W	6200N	07000W	6100N	06500W	5800N	04500W	6000N	00500W
42	YYC	LAX												
7	YYC	LON	6230N	08000W	6300N	07500W	6200N	07000W	6100N	06500W	5800N	04500W	5100N	00900W
14	YYC	PAR	6230N	08000W	6300N	07500W	6200N	07000W	6100N	06500W	5800N	04500W	4800N	00600W
7	YYC	SFO												
14	YYZ	AMS	4108N	06700W	4700N	05000W	5100N	00900W						
21	YYZ	FRA	4108N	06700W	4700N	05000W	5100N	00900W						
49	YYZ	LON	4108N	06700W	4700N	05000W	5100N	00900W						
7	YYZ	PAR	4108N	06700W	4700N	05000W	5100N	00900W						
7	YYZ	ROM	4108N	06700W	5100N	00900W								
14	YYZ	YVR												

Appendix D. HSCT Mission Profile Methodology

The aerodynamics performance programs are able to provide HSCT performance for a pure supersonic or a pure subsonic mission. A method was developed to accommodate the city-pair routes in the Emissions Study Network which consist of routes with multiple mixed subsonic and supersonic segments. The method takes six subsonic and supersonic mission profiles of varying range and uses regression analysis to develop generalized performance for each mission segment as a function of weight or some in some cases an average is used. A summary of the parameters by segment are:

Taxi-Out
Time: .167 (hr)
Distance: 0 (n miles)
Fuel Burn Rate: Average of 6 data points (lbs/hr)
NOX: Average of 6 data points for supersonic descent segment (lb/lb of fuel)
CO: Average of 6 data points for supersonic descent segment (lb/lb of fuel)
HC: Average of 6 data points for supersonic descent segment (lb/lb of fuel)

Take-off & Subsonic Climb
Speed: linear function of initial climb weight (n miles/hr)
Time: Distance/Speed (hr)
Distance: linear function of initial climb weight (n miles)
Fuel Burn: linear function of initial climb weight (lbs/hr)
NOX: Average of 6 data points for supersonic climb segment (lb/lb of fuel)
CO: Average of 6 data points for supersonic climb segment (lb/lb of fuel)
HC: Average of 6 data points for supersonic climb segment (lb/lb of fuel)
End Altitude: Average of 6 data points (ft)

Supersonic Climb
Speed: linear function of initial climb weight (n miles/hr)
Time: Distance/Speed (hr)
Distance: logarithmic function of initial climb weight (n miles)
Fuel Burn: linear function of initial climb weight (lbs/hr)
NOX: Average of 6 data points for supersonic climb segment (lb/lb of fuel)
CO: Average of 6 data points for supersonic climb segment(lb/lb of fuel)
HC: Average of 6 data points for supersonic climb segment (lb/lb of fuel)
End Altitude: Average of 6 data points (ft)

Supersonic Cruise
Speed: Average of 6 data points (n miles/hr)
Time: Distance/Speed (hr)
Distance: Total distance minus climb and descent segment distances (n miles)
Fuel Burn: linear function of average cruise weight (lbs/hr)
NOX: Average of 6 data points (lb/lb of fuel)
CO: Average of 6 data points (lb/lb of fuel)
HC: Average of 6 data points (lb/lb of fuel)
Altitude: linear function of cruise weight (ft)

Supersonic Descent
Time: Average of 6 data points (hr)
Distance: Average of 6 data points (n miles)
Fuel Burn: Average of 6 data points (lbs/hr)
NOX: Average of 6 data points for supersonic descent segment (lb/lb of fuel)
CO: Average of 6 data points for supersonic descent segment (lb/lb of fuel)
HC: Average of 6 data points for supersonic descent segment (lb/lb of fuel)
Altitude: linear function of subsonic cruise weight (ft)

Subsonic Descent & Landing
Time: Average of 6 data points (hr)
Distance: Average of 6 data points (n miles)
Fuel Burn: Average of 6 data points (lbs/hr)
NOX: Average of 6 data points for supersonic descent segment (lb/lb of fuel)
CO: Average of 6 data points for supersonic descent segment (lb/lb of fuel)
HC: Average of 6 data points for supersonic descent segment (lb/lb of fuel)

Taxi-In
Time: .083 (hr)
Distance: 0 (n miles)
Fuel Burn Rate: Average of 6 data points (lbs/hr)
NOX: Average of 6 data points for supersonic descent segment (lb/lb of fuel)
CO: Average of 6 data points for supersonic descent segment (lb/lb of fuel)
HC: Average of 6 data points for supersonic descent segment (lb/lb of fuel)

Reserve Fuel
Fuel: linear function of taxi weight (lbs)

The parameters are calculated in a similar manner for a subsonic mission without the supersonic climb and descent segment, and the appropriate data for the subsonic cruise segment.

For each city pair route in the Emissions Study Network, a set of segments were developed to fit within the overland and overwater points along the route. The mission landing weight is set equal to the operating empty weight + payload + reserve fuel. The take-off weight is set equal to the maximum take-off weight. The model iterates to solve for the take-off weight required to perform the mission and solves for the relevant mission parameters: time, distance, fuel, altitude, and emissions for each mission segment.

The resulting performance for the example discussed in the city pair routing section (Frankfurt - Bangkok) is shown in the following table. In this example, the altered path distance is in excess of the 5,000 nautical mile design range of the Emission Study Airplane, thus requiring a stop in Bahrain.

Table D-1. Mission Profile for FRA-BAH-BKK

Segment	Cumulative Distance (nm)	End Altitude (ft)	Cumulative Fuel (lb)
Taxi-out (FRA)	0	0	2933
Subsonic climb	41	36643	18894
Subsonic cruise	321	37401	35421
Supersonic climb	542	64988	63870
Supersonic cruise	1588	67117	115802
Supersonic descent	1710	40561	116594
Subsonic cruise	2576	42150	157384
Subsonic descent	2721	0	163161
Taxi-in (BAH)	2721	0	164281
Taxi-out (BAH)	0	0	2933
Subsonic climb	43	34662	20258
Supersonic climb & descent	176	35258	32635
Subsonic cruise	589	36264	58483
Supersonic climb	832	63916	89989
Supersonic cruise	3195	68675	206042
Supersonic descent	3317	42041	206834
Subsonic descent	3462	0	212611
Taxi-in (BKK)	3462	0	213731

Appendix E. Altitude Distribution of Emissions

This appendix contains the tables which summarize the different emission scenarios. For each of the scenarios considered, the fuel burned and emissions (NOx, CO, and hydrocarbons) were summed over latitude and longitude and tabulated as a function of altitude in 1 km altitude increments (the resolution of the data set).

Cumulative fractions of fuel burned and emissions were calculated from the ground up to provide a simple way to evaluate how the emissions were distributed vertically. In addition, the effective emission index for each altitude band was calculated and tabulated.

The global total of fuel burned and emissions were calculated and listed at the bottom of each table. Also, included is the effective emission index for NOx, CO, and hydrocarbons, globally averaged over all locations and altitudes.

For the charts shown, the notation 1.00E+08 is equivalent to 1.00×10^8. The emissions are in units of kilograms per year and the emission indices have units of grams of emissions per kilogram of fuel burned.

US Standard Atmosphere (1976) pressures and temperatures were used in the calculations. These altitudes correspond to the geopotential altitudes of the US Standard Atmosphere grid.

Table E-1. Fuel Burned, Emissions, Cumulative Fractions of Fuel Burned and Emissions, and Emission Indices as a Function of Altitude (Summed over Latitude and Longitude) for the Mach 2.4 (Nominal EI(NOx)=5) HSCT fleet only

Altitude Band (km)	Fuel (kg/year)	cum fuel (%)	NOx (kg/year)	cum NOx (%)	HC (kg/year)	cum HC (%)	CO (kg/year)	cum CO (%)	EI(NOx)	EI(HC)	EI(CO)
0 - 1	2.24E+09	2.9%	1.59E+07	3.2%	2.92E+06	10.3%	2.77E+07	11.8%	7.12	1.31	12.37
1 - 2	7.65E+08	3.9%	6.28E+06	4.4%	4.47E+05	11.9%	2.92E+06	13.1%	8.21	0.59	3.82
2 - 3	7.65E+08	4.9%	6.28E+06	5.7%	4.47E+05	13.5%	2.92E+06	14.4%	8.21	0.59	3.82
3 - 4	7.65E+08	5.9%	6.28E+06	7.0%	4.47E+05	15.1%	2.92E+06	15.6%	8.21	0.59	3.82
4 - 5	7.65E+08	6.9%	6.28E+06	8.2%	4.47E+05	16.6%	2.92E+06	16.9%	8.21	0.59	3.82
5 - 6	7.65E+08	7.9%	6.28E+06	9.5%	4.47E+05	18.2%	2.92E+06	18.1%	8.21	0.59	3.82
6 - 7	7.65E+08	8.9%	6.28E+06	10.7%	4.47E+05	19.8%	2.92E+06	19.4%	8.21	0.59	3.82
7 - 8	7.65E+08	9.9%	6.28E+06	12.0%	4.47E+05	21.4%	2.92E+06	20.6%	8.21	0.59	3.82
8 - 9	7.65E+08	10.9%	6.28E+06	13.2%	4.47E+05	23.0%	2.92E+06	21.9%	8.21	0.59	3.82
9 - 10	1.64E+09	13.1%	1.36E+07	16.0%	8.00E+05	25.8%	5.87E+06	24.4%	8.30	0.49	3.59
10 - 11	3.13E+09	17.2%	2.61E+07	21.2%	1.41E+06	30.8%	1.11E+07	29.1%	8.34	0.45	3.53
11 - 12	2.61E+09	20.6%	2.19E+07	25.6%	1.14E+06	34.8%	7.82E+06	32.5%	8.38	0.44	3.00
12 - 13	4.75E+09	26.8%	3.97E+07	33.5%	2.05E+06	42.0%	1.65E+07	39.5%	8.36	0.43	3.48
13 - 14	1.52E+09	28.8%	1.31E+07	36.1%	4.83E+05	43.8%	9.98E+05	40.0%	8.61	0.32	0.66
14 - 15	1.52E+09	30.8%	1.31E+07	38.7%	4.83E+05	45.5%	9.98E+05	40.4%	8.61	0.32	0.66
15 - 16	1.52E+09	32.8%	1.31E+07	41.4%	4.83E+05	47.2%	9.98E+05	40.8%	8.61	0.32	0.66
16 - 17	1.52E+09	34.7%	1.31E+07	44.0%	4.83E+05	48.9%	9.98E+05	41.3%	8.61	0.32	0.66
17 - 18	1.56E+09	36.8%	1.33E+07	46.6%	4.95E+05	50.6%	1.14E+06	41.7%	8.51	0.32	0.73
18 - 19	7.40E+09	46.5%	4.35E+07	55.3%	2.17E+06	58.3%	1.90E+07	49.9%	5.88	0.29	2.56
19 - 20	1.86E+10	70.8%	1.02E+08	75.7%	5.36E+06	77.2%	5.27E+07	72.4%	5.48	0.29	2.84
20 - 21	2.23E+10	100.0%	1.21E+08	100.0%	6.44E+06	100.0%	6.43E+07	100.0%	5.43	0.29	2.88
21 - 22	2.97E+07	100.0%	1.61E+05	100.0%	8.57E+03	100.0%	8.56E+04	100.0%	5.42	0.29	2.88
Global Total	7.64E+10		5.00E+08		2.83E+07		2.33E+08		6.54	0.37	3.05

Table E-2. Fuel Burned, Emissions, Cumulative Fractions of Fuel Burned and Emissions, and Emission Indices as a Function of Altitude (Summed over Latitude and Longitude) for the Mach 2.4 (Nominal EI(NOx)=15) HSCT fleet only

Altitude Band (km)	Fuel (kg/year)	cum fuel (%)	NOx (kg/year)	cum NOx (%)	HC (kg/year)	cum HC (%)	CO (kg/year)	cum CO (%)	EI(NOx)	EI(HC)	EI(CO)
0 - 1	2.24E+09	2.9%	3.32E+07	2.4%	2.92E+06	10.3%	2.77E+07	11.8%	14.86	1.31	12.37
1 - 2	7.65E+08	3.9%	1.74E+07	3.7%	4.47E+05	11.9%	2.92E+06	13.1%	22.70	0.59	3.82
2 - 3	7.65E+08	4.9%	1.74E+07	5.0%	4.47E+05	13.5%	2.92E+06	14.4%	22.70	0.59	3.82
3 - 4	7.65E+08	5.9%	1.74E+07	6.3%	4.47E+05	15.1%	2.92E+06	15.6%	22.70	0.59	3.82
4 - 5	7.65E+08	6.9%	1.74E+07	7.6%	4.47E+05	16.6%	2.92E+06	16.9%	22.70	0.59	3.82
5 - 6	7.65E+08	7.9%	1.74E+07	8.9%	4.47E+05	18.2%	2.92E+06	18.1%	22.70	0.59	3.82
6 - 7	7.65E+08	8.9%	1.74E+07	10.1%	4.47E+05	19.8%	2.92E+06	19.4%	22.70	0.59	3.82
7 - 8	7.65E+08	9.9%	1.74E+07	11.4%	4.47E+05	21.4%	2.92E+06	20.6%	22.70	0.59	3.82
8 - 9	7.65E+08	10.9%	1.74E+07	12.7%	4.47E+05	23.0%	2.92E+06	21.9%	22.70	0.59	3.82
9 - 10	1.64E+09	13.1%	2.86E+07	14.8%	8.00E+05	25.8%	5.87E+06	24.4%	17.50	0.49	3.59
10 - 11	3.13E+09	17.2%	4.74E+07	18.3%	1.41E+06	30.8%	1.11E+07	29.1%	15.16	0.45	3.53
11 - 12	2.61E+09	20.6%	4.69E+07	21.8%	1.14E+06	34.8%	7.82E+06	32.5%	17.98	0.44	3.00
12 - 13	4.75E+09	26.8%	6.74E+07	26.7%	2.05E+06	42.0%	1.65E+07	39.5%	14.17	0.43	3.48
13 - 14	1.52E+09	28.8%	3.89E+07	29.6%	4.83E+05	43.8%	9.98E+05	40.0%	25.61	0.32	0.66
14 - 15	1.52E+09	30.8%	3.89E+07	32.5%	4.83E+05	45.5%	9.98E+05	40.4%	25.61	0.32	0.66
15 - 16	1.52E+09	32.8%	3.89E+07	35.3%	4.83E+05	47.2%	9.98E+05	40.8%	25.61	0.32	0.66
16 - 17	1.52E+09	34.7%	3.89E+07	38.2%	4.83E+05	48.9%	9.98E+05	41.3%	25.61	0.32	0.66
17 - 18	1.56E+09	36.8%	3.96E+07	41.1%	4.95E+05	50.6%	1.14E+06	41.7%	25.32	0.32	0.73
18 - 19	7.40E+09	46.5%	1.30E+08	50.7%	2.17E+06	58.3%	1.90E+07	49.9%	17.60	0.29	2.56
19 - 20	1.86E+10	70.8%	3.05E+08	73.2%	5.36E+06	77.2%	5.27E+07	72.4%	16.44	0.29	2.84
20 - 21	2.23E+10	100.0%	3.63E+08	100.0%	6.44E+06	100.0%	6.43E+07	100.0%	16.26	0.29	2.88
21 - 22	2.97E+07	100.0%	4.83E+05	100.0%	8.57E+03	100.0%	8.56E+04	100.0%	16.26	0.29	2.88
Global Total	7.64E+10		1.36E+09		2.83E+07		2.33E+08		17.75	0.37	3.05

Table E-3. Fuel Burned, Emissions, Cumulative Fractions of Fuel Burned and Emissions, and Emission Indices as a Function of Altitude (Summed over Latitude and Longitude) for the Mach 2.0 (Nominal EI(NOx)=5) HSCT fleet only

Altitude Band (km)	Fuel (kg/year)	cum fuel (%)	NOx (kg/year)	cum NOx (%)	HC (kg/year)	cum HC (%)	CO (kg/year)	cum CO (%)	EI(NOx)	EI(HC)	EI(CO)
0 - 1	2.04E+09	2.6%	1.49E+07	3.2%	2.52E+06	9.2%	2.38E+07	10.1%	7.29	1.24	11.70
1 - 2	7.05E+08	3.5%	5.54E+06	4.3%	4.05E+05	10.6%	2.63E+06	11.2%	7.86	0.57	3.72
2 - 3	7.05E+08	4.4%	5.54E+06	5.5%	4.05E+05	12.1%	2.63E+06	12.3%	7.86	0.57	3.72
3 - 4	7.05E+08	5.3%	5.54E+06	6.7%	4.05E+05	13.6%	2.63E+06	13.5%	7.86	0.57	3.72
4 - 5	7.05E+08	6.2%	5.54E+06	7.9%	4.05E+05	15.1%	2.63E+06	14.6%	7.86	0.57	3.72
5 - 6	7.05E+08	7.1%	5.54E+06	9.0%	4.05E+05	16.5%	2.63E+06	15.7%	7.86	0.57	3.72
6 - 7	7.05E+08	8.0%	5.54E+06	10.2%	4.05E+05	18.0%	2.63E+06	16.8%	7.86	0.57	3.72
7 - 8	7.05E+08	8.9%	5.54E+06	11.4%	4.05E+05	19.5%	2.63E+06	17.9%	7.86	0.57	3.72
8 - 9	7.05E+08	9.8%	5.54E+06	12.6%	4.05E+05	21.0%	2.63E+06	19.0%	7.86	0.57	3.72
9 - 10	1.64E+09	11.9%	1.19E+07	15.1%	7.20E+05	23.6%	5.43E+06	21.3%	7.25	0.44	3.30
10 - 11	2.83E+09	15.4%	2.04E+07	19.4%	1.10E+06	27.6%	8.13E+06	24.8%	7.20	0.39	2.87
11 - 12	2.28E+09	18.3%	1.70E+07	23.0%	9.08E+05	30.9%	5.87E+06	27.3%	7.44	0.40	2.57
12 - 13	4.24E+09	23.7%	3.00E+07	29.4%	1.54E+06	36.5%	1.20E+07	32.4%	7.06	0.36	2.82
13 - 14	1.33E+09	25.4%	1.08E+07	31.7%	4.25E+05	38.0%	8.86E+05	32.7%	8.07	0.32	0.66
14 - 15	1.33E+09	27.1%	1.08E+07	34.0%	4.25E+05	39.6%	8.86E+05	33.1%	8.07	0.32	0.66
15 - 16	1.33E+09	28.8%	1.08E+07	36.3%	4.25E+05	41.1%	8.86E+05	33.5%	8.07	0.32	0.66
16 - 17	2.80E+09	32.4%	1.82E+07	40.2%	8.45E+05	44.2%	5.33E+06	35.8%	6.50	0.30	1.90
17 - 18	1.23E+10	48.1%	6.67E+07	54.3%	3.58E+06	57.2%	3.41E+07	50.2%	5.40	0.29	2.76
18 - 19	2.32E+10	77.5%	1.22E+08	80.3%	6.68E+06	81.5%	6.63E+07	78.4%	5.27	0.29	2.86
19 - 20	1.77E+10	100.0%	9.28E+07	100.0%	5.09E+06	100.0%	5.09E+07	100.0%	5.25	0.29	2.88
Global Total	7.87E+10		4.70E+08		2.75E+07		2.35E+08		5.98	0.35	2.99

Table E-4. Fuel Burned, Emissions, Cumulative Fractions of Fuel Burned and Emissions, and Emission Indices as a Function of Altitude (Summed over Latitude and Longitude) for the Mach 2.0 (Nominal EI(NOx)=15) HSCT fleet only

Altitude Band (km)	Fuel (kg/year)	cum fuel (%)	NOx (kg/year)	cum NOx (%)	HC (kg/year)	cum HC (%)	CO (kg/year)	cum CO (%)	EI(NOx)	EI(HC)	EI(CO)
0 - 1	2.04E+09	2.6%	2.95E+07	2.1%	2.52E+06	9.2%	2.38E+07	10.1%	14.47	1.24	11.70
1 - 2	7.05E+08	3.5%	1.51E+07	3.2%	4.05E+05	10.6%	2.63E+06	11.2%	21.34	0.57	3.72
2 - 3	7.05E+08	4.4%	1.51E+07	4.3%	4.05E+05	12.1%	2.63E+06	12.3%	21.34	0.57	3.72
3 - 4	7.05E+08	5.3%	1.51E+07	5.4%	4.05E+05	13.6%	2.63E+06	13.5%	21.34	0.57	3.72
4 - 5	7.05E+08	6.2%	1.51E+07	6.5%	4.05E+05	15.1%	2.63E+06	14.6%	21.34	0.57	3.72
5 - 6	7.05E+08	7.1%	1.51E+07	7.6%	4.05E+05	16.5%	2.63E+06	15.7%	21.34	0.57	3.72
6 - 7	7.05E+08	8.0%	1.51E+07	8.7%	4.05E+05	18.0%	2.63E+06	16.8%	21.34	0.57	3.72
7 - 8	7.05E+08	8.9%	1.51E+07	9.8%	4.05E+05	19.5%	2.63E+06	17.9%	21.34	0.57	3.72
8 - 9	7.05E+08	9.8%	1.51E+07	10.9%	4.05E+05	21.0%	2.63E+06	19.0%	21.34	0.57	3.72
9 - 10	1.64E+09	11.9%	3.42E+07	13.4%	7.20E+05	23.6%	5.43E+06	21.3%	20.79	0.44	3.30
10 - 11	2.83E+09	15.4%	5.95E+07	17.7%	1.10E+06	27.6%	8.13E+06	24.8%	21.04	0.39	2.87
11 - 12	2.28E+09	18.3%	4.93E+07	21.3%	9.08E+05	30.9%	5.87E+06	27.3%	21.61	0.40	2.57
12 - 13	4.24E+09	23.7%	8.86E+07	27.7%	1.54E+06	36.5%	1.20E+07	32.4%	20.88	0.36	2.82
13 - 14	1.33E+09	25.4%	3.20E+07	30.1%	4.25E+05	38.0%	8.86E+05	32.7%	23.98	0.32	0.66
14 - 15	1.33E+09	27.1%	3.20E+07	32.4%	4.25E+05	39.6%	8.86E+05	33.1%	23.98	0.32	0.66
15 - 16	1.33E+09	28.8%	3.20E+07	34.7%	4.25E+05	41.1%	8.86E+05	33.5%	23.98	0.32	0.66
16 - 17	2.80E+09	32.4%	5.43E+07	38.7%	8.45E+05	44.2%	5.33E+06	35.8%	19.37	0.30	1.90
17 - 18	1.23E+10	48.1%	2.00E+08	53.2%	3.58E+06	57.2%	3.41E+07	50.2%	16.18	0.29	2.76
18 - 19	2.32E+10	77.5%	3.66E+08	79.8%	6.68E+06	81.5%	6.63E+07	78.4%	15.79	0.29	2.86
19 - 20	1.77E+10	100.0%	2.78E+08	100.0%	5.09E+06	100.0%	5.09E+07	100.0%	15.74	0.29	2.88
Global Total	7.87E+10		1.38E+09		2.75E+07		2.35E+08		17.49	0.35	2.99

Table E-5. Fuel Burned, Emissions, Cumulative Fractions of Fuel Burned and Emissions, and Emission Indices as a Function of Altitude (Summed over Latitude and Longitude) for the 1990 Scheduled Passenger and Cargo Fleet

Altitude Band (km)	Fuel (kg/year)	cum fuel (%)	NOx (kg/year)	cum NOx (%)	HC (kg/year)	cum HC (%)	CO (kg/year)	cum CO (%)	EI(NOx)	EI(HC)	EI(CO)
0 - 1	1.09E+10	12.0%	1.32E+08	11.6%	3.99E+07	29.2%	1.54E+08	29.8%	12.11	3.65	14.09
1 - 2	2.62E+09	14.9%	4.14E+07	15.2%	6.45E+06	33.9%	2.38E+07	34.4%	15.79	2.46	9.08
2 - 3	2.40E+09	17.6%	4.01E+07	18.8%	6.14E+06	38.4%	2.12E+07	38.5%	16.71	2.56	8.81
3 - 4	2.80E+09	20.7%	5.04E+07	23.2%	6.09E+06	42.9%	2.00E+07	42.3%	17.96	2.17	7.14
4 - 5	2.36E+09	23.3%	3.92E+07	26.6%	6.31E+06	47.5%	1.94E+07	46.1%	16.57	2.67	8.22
5 - 6	2.31E+09	25.8%	3.68E+07	29.8%	6.79E+06	52.5%	2.06E+07	50.1%	15.93	2.94	8.90
6 - 7	2.40E+09	28.4%	3.73E+07	33.1%	6.83E+06	57.5%	2.01E+07	54.0%	15.51	2.84	8.34
7 - 8	2.56E+09	31.3%	3.67E+07	36.3%	7.44E+06	62.9%	2.15E+07	58.1%	14.35	2.91	8.40
8 - 9	2.79E+09	34.3%	3.65E+07	39.5%	7.06E+06	68.1%	2.05E+07	62.1%	13.09	2.53	7.36
9 - 10	4.61E+09	39.4%	5.93E+07	44.7%	7.94E+06	73.9%	2.28E+07	66.5%	12.86	1.72	4.95
10 - 11	2.82E+10	70.5%	3.05E+08	71.4%	1.95E+07	88.2%	8.41E+07	82.8%	10.79	0.69	2.98
11 - 12	2.58E+10	98.9%	3.14E+08	99.0%	1.47E+07	98.9%	7.96E+07	98.2%	12.15	0.57	3.08
12 - 13	4.69E+08	99.5%	5.10E+06	99.4%	4.47E+05	99.2%	1.26E+06	98.4%	10.89	0.95	2.70
13 - 14	3.82E+08	99.9%	4.83E+06	99.8%	1.80E+05	99.4%	6.89E+05	98.5%	12.64	0.47	1.80
14 - 15	3.95E+06	99.9%	3.65E+04	99.8%	2.22E+04	99.4%	1.59E+05	98.6%	9.24	5.62	40.14
15 - 16	3.95E+06	99.9%	3.65E+04	99.8%	2.37E+04	99.4%	1.69E+05	98.6%	9.24	5.99	42.80
16 - 17	3.75E+07	99.9%	6.67E+05	99.9%	2.92E+05	99.6%	2.55E+06	99.1%	17.78	7.77	68.00
17 - 18	4.97E+07	100.0%	8.96E+05	100.0%	4.10E+05	99.9%	3.60E+06	99.8%	18.01	8.24	72.40
18 - 19	1.43E+07	100.0%	2.58E+05	100.0%	1.22E+05	100.0%	1.07E+06	100.0%	18.01	8.52	74.86
Global Total	9.08E+10		1.14E+09		1.37E+08		5.17E+08		12.56	1.50	5.69

Table E-6. Fuel Burned, Emissions, Cumulative Fractions of Fuel Burned and Emissions, and Emission Indices as a Function of Altitude (Summed over Latitude and Longitude) for the 1990 Scheduled Turboprop Fleet

Altitude Band (km)	Fuel (kg/year)	cum fuel (%)	NOx (kg/year)	cum NOx (%)	HC (kg/year)	cum HC (%)	CO (kg/year)	cum CO (%)	EI(NOx)	EI(HC)	EI(CO)
0 - 1	4.42E+08	22.3%	2.88E+06	14.0%	3.78E+05	34.0%	3.69E+06	37.8%	6.52	0.86	8.35
1 - 2	2.28E+08	33.7%	2.10E+06	24.3%	1.50E+05	47.5%	1.19E+06	49.9%	9.21	0.66	5.21
2 - 3	2.71E+08	47.4%	2.91E+06	38.4%	1.29E+05	59.1%	1.17E+06	61.9%	10.75	0.48	4.32
3 - 4	3.23E+08	63.6%	3.70E+06	56.4%	1.57E+05	73.3%	1.19E+06	74.1%	11.43	0.49	3.68
4 - 5	3.91E+08	83.3%	4.51E+06	78.4%	1.96E+05	90.9%	1.29E+06	87.3%	11.54	0.50	3.30
5 - 6	2.72E+08	97.0%	3.90E+06	97.4%	8.83E+04	98.9%	9.54E+05	97.0%	14.34	0.33	3.51
6 - 7	4.48E+07	99.3%	3.83E+05	99.3%	9.45E+03	99.7%	2.32E+05	99.4%	8.55	0.21	5.17
7 - 8	1.43E+07	100.0%	1.47E+05	100.0%	3.30E+03	100.0%	5.76E+04	100.0%	10.26	0.23	4.03
Global Total	1.99E+09		2.05E+07		1.11E+06		9.77E+06		10.34	0.56	4.92

Table E-7. Fuel Burned, Emissions, Cumulative Fractions of Fuel Burned and Emissions, and Emission Indices as a Function of Altitude (Summed over Latitude and Longitude) for the 1990 Scheduled "Generic" Fleet

Altitude Band (km)	Fuel (kg/year)	cum fuel (%)	NOx (kg/year)	cum NOx (%)	HC (kg/year)	cum HC (%)	CO (kg/year)	cum CO (%)	EI(NOx)	EI(HC)	EI(CO)
0 - 1	1.07E+10	11.8%	1.25E+08	10.8%	2.97E+07	28.6%	1.60E+08	30.1%	11.68	2.77	14.97
1 - 2	2.57E+09	14.6%	3.87E+07	14.2%	4.81E+06	33.2%	2.40E+07	34.6%	15.08	1.87	9.37
2 - 3	2.33E+09	17.1%	3.71E+07	17.4%	4.54E+06	37.6%	2.12E+07	38.6%	15.94	1.95	9.12
3 - 4	2.74E+09	20.2%	4.73E+07	21.4%	4.63E+06	42.1%	2.11E+07	42.6%	17.24	1.69	7.69
4 - 5	2.27E+09	22.7%	3.62E+07	24.6%	4.44E+06	46.3%	1.95E+07	46.2%	15.91	1.95	8.59
5 - 6	2.21E+09	25.1%	3.41E+07	27.5%	4.92E+06	51.1%	2.03E+07	50.0%	15.43	2.23	9.17
6 - 7	2.32E+09	27.6%	3.52E+07	30.6%	4.93E+06	55.8%	1.65E+07	53.1%	15.14	2.12	7.10
7 - 8	2.52E+09	30.4%	3.50E+07	33.6%	5.17E+06	60.8%	2.44E+07	57.7%	13.89	2.05	9.68
8 - 9	2.72E+09	33.4%	3.53E+07	36.6%	4.52E+06	65.1%	2.12E+07	61.7%	12.98	1.66	7.79
9 - 10	4.42E+09	38.2%	6.05E+07	41.8%	4.74E+06	69.7%	2.18E+07	65.8%	13.69	1.07	4.93
10 - 11	2.73E+10	68.2%	2.93E+08	67.2%	1.53E+07	84.4%	7.75E+07	80.3%	10.73	0.56	2.84
11 - 12	2.88E+10	99.9%	3.78E+08	99.8%	1.53E+07	99.1%	9.73E+07	98.5%	13.14	0.53	3.38
12 - 13	1.85E+06	99.9%	1.49E+04	99.8%	1.72E+04	99.1%	9.29E+04	98.6%	8.03	9.29	50.12
13 - 14	2.26E+06	99.9%	1.91E+04	99.8%	1.89E+04	99.2%	1.09E+05	98.6%	8.44	8.37	48.24
14 - 15	3.95E+06	99.9%	3.65E+04	99.8%	2.22E+04	99.2%	1.59E+05	98.6%	9.24	5.62	40.14
15 - 16	3.95E+06	99.9%	3.65E+04	99.8%	2.37E+04	99.2%	1.69E+05	98.6%	9.24	5.99	42.80
16 - 17	3.75E+07	99.9%	6.67E+05	99.9%	2.92E+05	99.5%	2.55E+06	99.1%	17.78	7.77	68.00
17 - 18	4.97E+07	100.0%	8.96E+05	100.0%	4.10E+05	99.9%	3.60E+06	99.8%	18.01	8.24	72.40
18 - 19	1.43E+07	100.0%	2.58E+05	100.0%	1.22E+05	100.0%	1.07E+06	100.0%	18.01	8.52	74.86
Global Total	9.11E+10		1.16E+09		1.04E+08		5.33E+08		12.72	1.14	5.85

Table E-8. Fuel Burned, Emissions, Cumulative Fractions of Fuel Burned and Emissions, and Emission Indices as a Function of Altitude (Summed over Latitude and Longitude) for the 2015 Scheduled Passenger Fleet, assuming no HSCT fleet exists

Altitude Band (km)	Fuel (kg/year)	cum fuel (%)	NOx (kg/year)	cum NOx (%)	HC (kg/year)	cum HC (%)	CO (kg/year)	cum CO (%)	EI(NOx)	EI(HC)	EI(CO)
0 - 1	2.63E+10	10.7%	2.58E+08	11.5%	2.97E+07	32.2%	3.41E+08	31.4%	9.81	1.13	12.97
1 - 2	6.54E+09	13.4%	8.19E+07	15.2%	5.44E+06	38.2%	5.89E+07	36.8%	12.53	0.83	9.01
2 - 3	5.65E+09	15.7%	6.85E+07	18.2%	4.67E+06	43.2%	5.01E+07	41.4%	12.12	0.83	8.86
3 - 4	7.37E+09	18.7%	9.78E+07	22.6%	4.04E+06	47.6%	4.38E+07	45.5%	13.27	0.55	5.95
4 - 5	6.06E+09	21.2%	7.36E+07	25.9%	4.20E+06	52.2%	4.55E+07	49.6%	12.14	0.69	7.51
5 - 6	5.76E+09	23.5%	6.69E+07	28.9%	4.29E+06	56.9%	4.63E+07	53.9%	11.62	0.75	8.05
6 - 7	5.19E+09	25.7%	5.93E+07	31.5%	3.80E+06	61.0%	4.08E+07	57.7%	11.43	0.73	7.86
7 - 8	5.62E+09	28.0%	6.11E+07	34.3%	4.20E+06	65.6%	4.50E+07	61.8%	10.89	0.75	8.02
8 - 9	6.29E+09	30.5%	6.62E+07	37.2%	4.46E+06	70.4%	4.74E+07	66.2%	10.53	0.71	7.55
9 - 10	7.38E+09	33.5%	7.22E+07	40.4%	4.44E+06	75.2%	4.60E+07	70.4%	9.78	0.60	6.24
10 - 11	5.04E+10	54.1%	4.02E+08	58.4%	7.29E+06	83.2%	1.05E+08	80.1%	7.99	0.14	2.09
11 - 12	1.12E+11	100.0%	9.31E+08	100.0%	1.55E+07	100.0%	2.16E+08	100.0%	8.29	0.14	1.92
Global Total	2.45E+11		2.24E+09		9.20E+07		1.09E+09		9.14	0.38	4.43

Table E-9. Fuel Burned, Emissions, Cumulative Fractions of Fuel Burned and Emissions, and Emission Indices as a Function of Altitude (Summed over Latitude and Longitude) for the 2015 Scheduled Passenger Fleet, assuming a 500 Mach 2.4 HSCT fleet exists

Altitude Band (km)	Fuel (kg/year)	cum fuel (%)	NOx (kg/year)	cum NOx (%)	HC (kg/year)	cum HC (%)	CO (kg/year)	cum CO (%)	EI(NOx)	EI(HC)	EI(CO)
0 - 1	2.49E+10	11.9%	2.36E+08	12.8%	3.97E+07	33.9%	3.45E+08	33.3%	9.47	1.59	13.88
1 - 2	6.28E+09	14.9%	7.81E+07	17.0%	8.57E+06	41.2%	6.20E+07	39.3%	12.43	1.36	9.88
2 - 3	5.42E+09	17.4%	6.44E+07	20.5%	6.57E+06	46.8%	5.15E+07	44.3%	11.90	1.21	9.50
3 - 4	7.00E+09	20.8%	9.05E+07	25.4%	5.46E+06	51.5%	4.43E+07	48.5%	12.94	0.78	6.33
4 - 5	5.81E+09	23.5%	6.90E+07	29.1%	5.81E+06	56.4%	4.64E+07	53.0%	11.88	1.00	7.98
5 - 6	5.51E+09	26.2%	6.22E+07	32.5%	6.03E+06	61.6%	4.73E+07	57.6%	11.28	1.09	8.59
6 - 7	4.94E+09	28.5%	5.53E+07	35.5%	4.47E+06	65.4%	4.05E+07	61.5%	11.19	0.90	8.19
7 - 8	5.35E+09	31.1%	5.65E+07	38.6%	5.18E+06	69.8%	4.48E+07	65.8%	10.56	0.97	8.38
8 - 9	5.99E+09	33.9%	6.10E+07	41.9%	6.05E+06	75.0%	4.80E+07	70.5%	10.19	1.01	8.01
9 - 10	6.53E+09	37.0%	6.15E+07	45.2%	5.94E+06	80.1%	4.59E+07	74.9%	9.41	0.91	7.02
10 - 11	4.07E+10	56.4%	3.02E+08	61.6%	7.99E+06	86.9%	9.12E+07	83.7%	7.43	0.20	2.24
11 - 12	9.14E+10	100.0%	7.09E+08	100.0%	1.54E+07	100.0%	1.69E+08	100.0%	7.76	0.17	1.85
Global Total	2.10E+11		1.85E+09		1.17E+08		1.04E+09		8.80	0.56	4.94

Table E-10. Fuel Burned, Emissions, Cumulative Fractions of Fuel Burned and Emissions, and Emission Indices as a Function of Altitude (Summed over Latitude and Longitude) for the 2015 Scheduled Cargo Fleet

Altitude Band (km)	Fuel (kg/year)	cum fuel (%)	NOx (kg/year)	cum NOx (%)	HC (kg/year)	cum HC (%)	CO (kg/year)	cum CO (%)	EI(NOx)	EI(HC)	EI(CO)
0 - 1	4.24E+08	7.5%	4.04E+06	8.2%	1.05E+06	29.4%	7.36E+06	26.6%	9.52	2.47	17.35
1 - 2	1.04E+08	9.4%	1.33E+06	10.9%	1.84E+05	34.5%	1.24E+06	31.1%	12.81	1.77	11.97
2 - 3	1.02E+08	11.2%	1.36E+06	13.7%	1.95E+05	40.0%	1.26E+06	35.6%	13.32	1.90	12.36
3 - 4	1.30E+08	13.5%	1.78E+06	17.3%	1.64E+05	44.6%	1.12E+06	39.7%	13.71	1.27	8.65
4 - 5	9.27E+07	15.1%	1.15E+06	19.7%	1.71E+05	49.4%	1.14E+06	43.8%	12.36	1.84	12.30
5 - 6	9.62E+07	16.8%	1.15E+06	22.0%	1.78E+05	54.4%	1.17E+06	48.0%	11.99	1.85	12.16
6 - 7	9.69E+07	18.5%	1.15E+06	24.4%	1.76E+05	59.3%	1.13E+06	52.1%	11.83	1.82	11.70
7 - 8	1.05E+08	20.4%	1.15E+06	26.7%	1.93E+05	64.8%	1.22E+06	56.5%	10.97	1.84	11.59
8 - 9	1.12E+08	22.4%	1.17E+06	29.1%	1.91E+05	70.1%	1.19E+06	60.8%	10.52	1.71	10.68
9 - 10	1.11E+08	24.3%	1.10E+06	31.4%	2.00E+05	75.8%	1.20E+06	65.2%	9.94	1.81	10.86
10 - 11	6.54E+08	35.9%	5.71E+06	43.0%	2.38E+05	82.4%	1.94E+06	72.2%	8.72	0.36	2.97
11 - 12	3.62E+09	100.0%	2.80E+07	100.0%	6.26E+05	100.0%	7.69E+06	100.0%	7.73	0.17	2.13
Global Total	5.64E+09		4.91E+07		3.56E+06		2.77E+07		8.69	0.63	4.90

Table E-11. Fuel Burned, Emissions, Cumulative Fractions of Fuel Burned and Emissions, and Emission Indices as a Function of Altitude (Summed over Latitude and Longitude) for the 2015 Scheduled Turboprop Fleet

Altitude Band (km)	Fuel (kg/year)	cum fuel (%)	NOx (kg/year)	cum NOx (%)	HC (kg/year)	cum HC (%)	CO (kg/year)	cum CO (%)	EI(NOx)	EI(HC)	EI(CO)
0 - 1	9.88E+08	23.9%	7.28E+06	16.5%	2.19E+06	30.1%	8.84E+06	36.6%	7.36	2.22	8.94
1 - 2	5.60E+08	37.4%	6.25E+06	30.6%	1.13E+06	45.7%	2.98E+06	49.0%	11.16	2.02	5.33
2 - 3	5.60E+08	50.9%	6.62E+06	45.6%	9.60E+05	58.9%	2.76E+06	60.4%	11.83	1.72	4.92
3 - 4	6.35E+08	66.3%	7.55E+06	62.7%	1.09E+06	73.9%	2.87E+06	72.3%	11.89	1.71	4.52
4 - 5	7.51E+08	84.4%	8.72E+06	82.4%	1.47E+06	94.1%	3.09E+06	85.1%	11.61	1.95	4.11
5 - 6	4.85E+08	96.1%	6.49E+06	97.1%	4.02E+05	99.6%	2.33E+06	94.8%	13.37	0.83	4.81
6 - 7	1.21E+08	99.1%	9.45E+05	99.2%	1.95E+04	99.9%	1.03E+06	99.1%	7.81	0.16	8.51
7 - 8	3.85E+07	100.0%	3.41E+05	100.0%	9.78E+03	100.0%	2.27E+05	100.0%	8.86	0.25	5.89
Global Total	4.14E+09		4.42E+07		7.27E+06		2.41E+07		10.68	1.76	5.83

Appendix F. 3-Dimensional Scenario Data Format

The three dimensional emission scenario data files calculated by Boeing were delivered to NASA Langley electronically in the following format:

i, j, k; fuel(lb/day); NOx(lb/day); CO(lb/day); HC(lb/day)

Only non-zero values are included in the ASCII data files.

Altitude:

Index k means emissions in the band from altitude k to k+1
i.e. index 19 is emissions in the 19-20 km band
Values run from 0 to 22

Latitude:

Index i means emissions in the band from latitude i to i+1
values run from 0 to 179

For i<=89 northern hemisphere
index 0 is emissions from equator to 1 degree N

For i>=90 southern hemisphere
index 90 is emissions from equator to 1 degree S
index 179 is emissions from 89S-90S

Longitude: Wrap all the way around the globe.

Index j means emissions in the longitude band j to j+1
values run from 0 to 359

For j<=179 east of prime meridian
index 0 is emissions from 0-1E
index 179 is emissions from 179E-180E

For j>=180 west of prime meridian
index 180 is emissions from -180W - -179W
index 359 is emissions from -1W - 0

Appendix G. Description of Global Atmospheric Emissions Code (GAEC)

Overview

The function of the Global Atmospheric Emissions Code is to accurately calculate the distribution of emissions into the atmosphere from specific airplanes flying specific routes which are identified by origin and destination city-pairs. GAEC was developed to combine functions in two Boeing programs that constitute the standard for the calculation of emissions at Boeing and to add the capability of calculating the distribution of emissions in the atmosphere. Improvement in efficiency was necessary in order to accommodate the volume of data necessary to evaluate the global 1990 and projected 2015 fleets. Simplifying assumptions not considered critical were required.

The GAEC program uses files of airplane performance data and engine specific emissions data. The program generates a three-dimensional mesh representing the atmosphere between the surface of the earth and a sphere at 22 kilometer altitude. Each cell in the atmosphere mesh has dimensions of one degree latitude by one degree longitude by one kilometer altitude. The program "flies" each airplane-route and calculates cumulative sums of fuel, NOx, HC, and CO emissions for each atmospheric cell crossed enroute. Output from the program consists of cell emissions and cell indices identifying the latitude, longitude and altitude of the cell. Only data for cells crossed by the routes are included in the output.

The Global Atmospheric Emissions Code handles two types of airplane performance and route data, that of the BMAP type and that of the "non-BMAP" type. BMAP (Boeing Mission Analysis Program) is the Boeing standard for calculating airplane performance (gross weight and fuel burn rate vs. altitude vs. distance) for a given route distance. The BMAP type solution uses two data files for each analysis airplane. The performance data file contains detailed performance data for a wide range of operating conditions and the route file contains all city-pairs and departure frequencies defining the routes. The non-BMAP solution uses a single data file containing simplified performance and emission data for each specific route. The non-BMAP solution is used when detailed performance data is not available and when there are relatively few routes. All airplanes analyzed in this study were of the BMAP solution type with the exception of the HSCT airplanes and the Concorde.

In both the BMAP and non-BMAP solutions, the general solution procedure is the same. The basic steps in the process are listed below.

For each city-pair

1. The three letter origin and destination codes are used to identify the waypoint coordinates (latitude, longitude, and altitude) from an airport description array.

2. Great circle distance is calculated between the waypoints (non-BMAP analysis allows waypoints between the origin and destination).

3. A set of discrete coordinate points (latitude, longitude vs. distance) are generated at 20 nmi intervals along the route. These points are used to interpolate coordinates where the flight path crosses atmospheric cell boundaries.

4. For each flight condition, tables of altitude, fuel, fuel burn rate (BMAP type only), and emissions (non-BMAP type only) vs. distance are calculated.

5. Distances to Route / Cell boundary intercept points are determined by interpolating on the step 3 data.

6. Performance data (airplane gross weight, fuel burn rate (BMAP type only) and emissions (non-BMAP type only) are interpolated at the route / cell boundary intercept points using the data from step 4 and step 5.

7. Emissions indices (lb emissions/ 1000 lb fuel) are interpolated from the tables of emissions indices vs. fuel flow rate (BMAP type only). The total fuel for a cell is the difference in the airplane gross weight from the coordinates at which it enters the cell to the coordinates at which it exits the cell.

General assumptions made within the GAEC program include the following:

1. The earth is assumed to be a sphere with a radius of 3444 nmi.

2. All flights follow a great circle route between city pairs or intermediate waypoints.

3. Altitude does not contribute to the flight distance. Distance is calculated assuming a great circle route at sea level.

4. Prevailing wind speeds are assumed to be zero.

5. Cruise distance is what is left over after the climb and descent distances are calculated. For short routes, an iteration is performed on cruise altitude and climb and descent distance calculations until the sum of the climb distance and descent distances is less than or equal to the total route distance. Peak altitude is then the altitude at which this distance condition is met.

6. Step cruises are not modeled. Instead, it is assumed that the airplane climbs linearly from the initial cruise altitude to the final cruise altitude over the cruise distance.

<u>Detailed Discussion - BMAP Type Analysis</u>

The GAEC "BMAP" type solution uses detailed airplane performance data from the Boeing Mission Analysis Program (BMAP) database files. This data provides time, distance, and fuel data vs. altitude vs. gross weight for climbout, climb, and descent conditions and fuel mileage (nmi/lb fuel) vs. Mach number vs. gross weight vs. altitude for cruise conditions. Additional data was added for calculating takeoff gross weight as a function of route distance, initial cruise altitude as a function of route distance and fuel burn rates and times for taxi-out, taxi-in, and approach-land flight conditions.

The solution process is outlined below.

For each analysis airplane:

1. The BMAP performance data is read from the airplane specific database file.

2. The engine performance data for the specific engine on the current airplane is read.

For each route flown by the airplane:

1. The coordinates (latitude, longitude, and altitude) of the origin and destination city-pair are determined from the airport description array.

2. Great circle route constants are calculated for the route defined by the city-pair coordinates.

3. A set of discrete points (latitude and longitude vs. distance from the origin) are calculated along the great circle route. These points are used for interpolation of the points where the airplane path crosses atmospheric cell boundaries. The program calculates one point every 20 nmi (minimum of 12 points, maximum of 400 points).

4. The takeoff gross weight is calculated as a function of the route distance.

For each flight condition, the procedure is to generate tables of gross weight, fuel burn rate, and altitude vs. distance. Distances to latitude and longitude cell boundaries intercepted during the flight condition are interpolated from the discrete route point data and distances to the altitude cell boundaries are interpolated from the altitude vs. distance data. The airplane gross weight, fuel burn rate, and additional coordinate data are interpolated at each of the intercept points. Once all the flight conditions are processed, the emissions are calculated. The emissions calculation process is discussed in a later section.

<u>Taxi-out:</u> Coordinates for the taxi-out condition are the origin airport coordinates. The fuel burn rate is read directly from the input data and the total fuel consumed is calculated from the fuel burn rate multiplied by the time in taxi-out condition.

Climbout: The gross weight of the airplane at climbout is the takeoff gross weight minus the weight of fuel burned during taxi-out. Given the climbout gross weight, time, distance, and fuel to complete the climbout to the given climbout altitude are interpolated from the tables of fuel, time, and distance vs. gross weight. The fuel burn rate is assumed constant as climbout fuel divided by climbout time. Climbout fuel and altitude are assumed to be a linear function of distance for purposes of determining route/cell boundary intercept coordinates and performance data at the intercept points.

Climb: The gross weight of the airplane is assumed constant for the entire climb and is equal to the climbout gross weight minus the weight of fuel burned during climbout. The initial cruise (end-of-climb) altitude is interpolated from the BMAP file data as a function of route distance. Tables of time, altitude, and fuel vs. distance are created by interpolating the climb data at the climb gross weight value. A table of fuel burn vs distance is generated from the fuel vs. distance and time vs. distance tables. The distance to the end-of-climb is interpolated from the initial cruise altitude in the altitude vs. distance table. The route/cell boundary intercept coordinates are interpolated and the performance data of gross weight and fuel burn rate are interpolated from the generated tables.

Cruise: The first step in calculating the performance for the cruise flight condition is to determine the distance to the end of cruise. The end-of-cruise distance is calculated as the route distance minus the distance to descend. It is necessary to estimate the gross weight of the airplane during descent in order to calculate the descent distance from the end-of- cruise altitude. The descent gross weight is estimated to be the zero-distance gross weight from the takeoff gross weight vs. route distance table. A table of descent distance vs. altitude is generated and the descent distance is interpolated in the table from the end-of-cruise altitude and destination altitude.

Altitude is assumed to vary linearly with distance from initial cruise altitude to the final cruise altitude. Initial cruise altitude is interpolated from the table of initial cruise altitude vs. route distance. This table ramps up to a maximum value (typically 39,000 feet) and then declines with distance as airplane takeoff gross weight increases. If the route length is less than the distance to the maximum altitude value then the cruise altitude is constant at the interpolated value. If the route length is greater than the distance to the maximum altitude value then the end-of-cruise altitude is the maximum altitude value. The route/cell boundary intercept points are interpolated and the performance data of gross weight and fuel burn rate are calculated at the intercept points. The cruise performance data is interpolated from tables of NAM (nautical air mileage) vs. Mach number vs. altitude vs. gross weight. The Mach number and corresponding fuel mileage values are interpolated from these tables, using the altitude and gross weight at the coordinate that the airplane enters the cell. Given the distance traversed in each cell, the fuel used is calculated from the fuel mileage divided by the distance traversed in the cell. The time to traverse the cell is required in order to determine the fuel burn rate in the cell. Time is derived from the velocity (Mach relationship) and cell traverse distance and the average fuel burn rate in the cell is calculated from the fuel consumed in the cell divided by the time required to traverse the cell.

Descent: The gross weight of the airplane is assumed constant for the entire descent and is equal to the gross weight at the end of cruise. Tables of time, altitude, and fuel vs. distance are created by interpolating the descent data at the descent gross weight value. A table of fuel burn vs. distance is generated from the fuel vs. distance and time vs. distance tables. The route/cell boundary intercept coordinates are interpolated and the performance data of gross weight and fuel burn rate are interpolated from the generated tables.

Approach and Land: Coordinates for the Approach and Land condition are the destination airport coordinates. The fuel burn rate is read directly from the input data and the total fuel consumed is calculated from the fuel burn rate multiplied by the time in Approach condition.

Taxi-in: Coordinates for the taxi-in condition are the destination airport coordinates. The fuel burn rate is read directly from the input data and the total fuel consumed is calculated from the fuel burn rate multiplied by the time in taxi-in condition.

Emissions: Once the performance data of fuel burn rate and total fuel burn for each cell along the flight profile has been calculated, the emissions data for each cell is calculated.

Engine emissions data (emissions indices vs. fuel flow rate were obtained from the ICAO data sheets and also directly from the engine vendors. These data were fitted to linear relationships on a log-log scale. Given the fuel flow rate at discrete locations along the flight path, the emissions indices for NOx, HC, and CO were interpolated from these emissions graphs. The ICAO emissions data is test data corrected to standard day, sea level conditions. This data was corrected for altitude using the following relationships.

First the fuel flow was corrected to the test conditions:

$$wf(\text{sea level}) = wf / \text{theta}^{1.5}$$

where

wf(sea level)	= the fuel flow corrected to the sea level test condition
wf	= the actual fuel flow rate at altitude
theta	= the ratio of the ambient temperature at altitude and the temperature at sea level, standard day conditions

Using the wf(sea level) value, the emissions indices were then interpolated from the tables. The emissions indices corrected for altitude were calculated using the relationships below.

EICO(alt) = EICO(s.l.) / delta ** 0.4
EIHC(alt) = EIHC(s.l.) / delta ** 0.4
EINOx(alt) = EINOx(s.l.) * theta * EH

EICO(alt), EIHC(alt), and EINOx(alt) are the emissions indices at altitude

EICO(s.l.), EIHC(s.l.), and EINOx(s.l.) are the emissions indices at sea level.

delta is the ratio of the atmospheric pressure at altitude divided by the atmospheric pressure at sea level

EH is the specific humidity correction at altitude corresponding to a 60% relative humidity

The weight of emissions for each cell is then calculated from the EI value multiplied by the total fuel consumed while traversing the cell.

Each cell's emissions and fuel burn for the current route are added to the cell totals for all routes.

The next route flown by the airplane is processed until all routes have been "flown". A file containing the cell emissions totals is written for each airplane

Detailed Discussion - Non-BMAP Type Analysis

The GAEC "NONBMAP" type solution uses data that is far less detailed than that used in the "BMAP" performance files. This solution method was developed specifically for the HSCT airplane where the performance models generate only cumulative emissions data at the end of each flight condition. This data specifically gives distance from origin, altitude, cumulative fuel burn, and cumulative emissions (NOx, HC, and CO) at the end of each segment (climb, cruise, etc.) for each city pair flown. Each route has a city pair that define the origin and destination of the flight and waypoint coordinates (latitude and longitude) that define the endpoints of segments traveled enroute. This method was also used for the analysis of the Concorde which flies few routes and for which Boeing has only rough performance data.

The solution process is outlined below.

For each set of city pair and performance data the following steps are done.

1.) The coordinates (latitude, longitude, and altitude) of the origin and destination city-pair are determined from the airport description array.

2.) The route is divided into segments defined by waypoints and city-pair coordinates. For each route segment defined by the waypoints, the following process is completed:

a.) Great circle route constants are calculated for the segment defined by the waypoint coordinates.

b.) A set of discrete points (latitude and longitude vs. distance from the origin) are calculated along the great circle route between the segment endpoints. These points are used for interpolation of the points where the airplane path crosses atmospheric cell boundaries. The program calculates one point every 20 nmi (minimum of 12 points, maximum of 400 points).

c.) Interpolating on the discrete data from the previous step, the distances to the route / cell latitude and longitude intercept points are calculated.

d.) The altitudes at these points are interpolated from the input table of altitude vs. distance.

e.) Interpolating on the input table of altitude vs. distance, the distances to route / cell altitude intercept points from the origin are calculated. Using the discrete route segment coordinate data, the latitude and longitude coordinates at the route/cell altitude boundary intercept points are interpolated.

f.) Using the input table of altitude vs. distance, the value of altitude at each of the cell boundary intercept points is interpolated.

g.) The coordinates of the route/cell intercept points in the next segment are calculated. Using the input tables of cumulative fuel and emissions vs. distance along the route, the fuel burned and emissions dispersed within each cell traversed along the flight path is interpolated. The cell emissions for the current route are then added to the total cell emissions for all routes.

Checkouts

As discussed previously, the GAEC code was written to be a shortcut for the standard Boeing emissions analysis process and, as such, some basic assumptions were made. In order to validate the GAEC code against the standard codes BMAP and EMIT, a set of test cases were run using both GAEC and the BMAP-EMIT process. The results of the test were described briefly in Section 3 and shown in Table 3-1..

Four routes for a particular aircraft/engine combination were analyzed by both methods using the operating conditions assumed for the global emissions calculations (no winds, International Standard Atmosphere conditions, 70% full passenger payload, 200 lb per passenger, etc.). The results of this analysis were discussed briefly in Section 3 and shown in Table 3-1. The table shows the total fuel burned and emissions generated for each portion of the flight segment as calculated in both the BMAP-EMIT analysis and the GAEC analysis. In all of the test cases, the difference between total fuel or total emissions was less than 2% when the GAEC solution was compared to the BMAP-EMIT solution. The differences in Table 3-1 are the percentages relative to the BMAP-EMIT solutions. The most obvious discrepancy in the data is seen in the GAEC approach data where the HC and CO emissions were overestimated by 25% and NOx was overestimated by 13%. This is most likely due to the approach performance averaging in GAEC. The approach analysis in BMAP uses two thrust (fuel flow) settings starting near idle and then increasing as the airplane gets closer to landing. GAEC assumes an average power setting (fuel flow) for the entire approach-land segment which results in higher overall emissions. For purposes of this analysis, when the emissions for approach were compared to the total emissions for the flight, the differences in the approach calculations were acceptable. All other differences were accepted as being well within the overall tolerances for the study.

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13. ABSTRACT *(Maximum 200 words)*

This report describes the development of a stratospheric emissions effects database (SEED) of aircraft fuel burn and emissions from projected Year 2015 subsonic aircraft fleets and from projected fleets of high-speed civil transports (HSCT's). This report also describes the development of a similar database of emissions from Year 1990 scheduled commercial passenger airline and air cargo traffic.

The objective of this work was to initiate, develop, and maintain an engineering database for use by atmospheric scientists conducting the Atmospheric Effects of Stratospheric Aircraft (AESA) modeling studies. Fuel burn and emissions of nitrogen oxides (NOx as NO2), carbon monoxide, and hydrocarbons (as CH4) have been calculated on a 1-degree latitude x 1-degree longitude x 1-kilometer altitude grid and delivered to NASA as electronic files. This report describes the assumptions and methodology for the calculations and summarizes the results of these calculations.

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