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Year 2015 Aircraft Emission Scenario for Scheduled Air Traffic

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Executive Summary

This report describes the development of a new emission scenario for scheduled air traffic in 2015. Passenger demand, aircraft performance, and aircraft engine emission characteristics were forecast to 2015. Fuel burned and emissions of nitrogen oxides (NOx as NO_2), carbon monoxide, and hydrocarbons 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. This emission scenario was developed under the NASA Integrated Wing Technology contract NAS1-20267, Task Assignment 5 and will be available for use by atmospheric scientists conducting the Atmospheric Effects of Aviation Project (AEAP) modeling studies.

Global jet fuel use by scheduled air traffic was projected to be 684 million kg/day, which is an increase of 164 % over that calculated previously for 1992. Global NOx emissions were calculated to be 9.7 million kg/day, which is an increase of 187% compared to 1992. Total hydrocarbon emissions were calculated to be slightly lower (by 11%) than 1992, while total carbon monoxide emissions were calculated to increase by 125%.

The global fuel consumption in this forecast of 2015 is approximately 3.9% lower than that projected previously for 2015. Global NOx emissions are calculated to be 46% higher in this forecast compared to the earlier 2015 scenario due to changes in assumptions regarding the level of future NOx reduction technology.

In this work, the 2015 scheduled fleet was represented by a large number of current and projected aircraft (110 compared to 10 generic types in the earlier study) and a much wider range of engine characteristics. Unlike the earlier study, retirement and replacement of existing aircraft was treated explicitly (the earlier study assumed that the average technology in 2015 corresponded to new 2005 aircraft). The current study also considered in more depth how new emissions technology would be introduced into the fleet, rather than assuming a dramatic improvement across all engine types. Differences in calculation methodology between the two studies also accounted for some of the differences in the results.

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GLOSSARY

AEAP	Atmospheric Effects of Aviation Project
ANCAT	Abatement of Nuisance Caused by Air Traffic
APU	Auxiliary power unit
BMAP	Boeing Mission Analysis Process
CAEP	ICAO Committee on Aviation Environmental Protection
CMO	Boeing Current Market Outlook
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DAC	Dual Annular Combustor
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)
GAEC	Global Atmospheric Emissions Code
GDP	Gross Domestic Product
GE	General Electric
HC	Unburned hydrocarbon
H_2O	Water
HSCT	High Speed Civil Transport
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 on a given flight
LTO cycle	Landing takeoff cycle
NASA	National Aeronautics and Space Administration (USA)
nmi	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)
SO_2	Sulfur dioxide
TOGW	Takeoff gross weight
ton	2000 pounds
USSR	Union of Soviet Socialist Republics

1.0 Introduction

In recent years there has been growing concern about how human activity may be affecting the global atmosphere and the influence that these atmospheric changes may have on the global climate. The United Nations Intergovernmental Panel on Climate Change (IPCC) is currently conducting an international assessment on “Aviation and the Global Atmosphere” and assessment programs on the atmospheric effects of aircraft emissions are underway in both the United States (Friedl, 1997) and Europe (Schumann, 1995; Brasseur, *et al.*, 1997). Within the United States, the NASA Atmospheric Effects of Aviation Project (AEAP) has been created to direct the assessment effort. In support of the NASA AEAP project, global inventories of past and projected future aircraft emissions have been calculated and used as input to global atmospheric chemistry models to assess aircraft-induced perturbations to the atmosphere.

Three-dimensional (latitude, longitude, pressure altitude) inventories of aircraft emissions have been developed previously within the NASA program and the European ANCAT (Abatement of Nuisance Caused by Air Traffic) project. The ANCAT results have been reported earlier (Gardner, *et al.*, 1997) and have recently been updated (Gardner, 1998). The ANCAT database has covered two time periods, 1991-92 and 2015.

The NASA-sponsored work has looked at historical data (1976, 1984, and 1992) and projections to the year 2015, both with and without fleets of high speed civil transports. These databases have included scheduled [i.e., listed in the Official Airline Guide (OAG)] air traffic, charter, military, general aviation, and non-OAG scheduled traffic within the former USSR and China. Fuel burned, plus emissions of nitrogen oxides (NOx), hydrocarbons, and carbon monoxide (CO) have been calculated onto a 1 degree latitude x 1 degree longitude x 1 km pressure altitude grid. The previous NASA studies are summarized in Table 1-1.

Earlier, Baughcum *et al.* (1994) developed a global emissions projection for scheduled subsonic air traffic for 2015. This work was updated by Baughcum and Henderson in 1995 to remedy a minor error in methodology. In the current study, the work of Baughcum and Henderson (1995) is updated to account for the latest passenger demand and technology forecasts. This report, summarizes the methodology and presents the results of this latest year 2015 projection. These results are then compared with the previously published results and the reasons for the differences are discussed.

Table 1-1. Summary of previous NASA aircraft emission inventory studies.

Traffic Year	Sector	References
1976	Scheduled	Baughcum, *et al.*, 1996b
	Charter, military, general aviation, former USSR/China	Mortlock and Van Alstyne, 1998
1984	Scheduled	Baughcum, *et al.*, 1996b
	Charter, military, general aviation, former USSR/China	Mortlock and Van Alstyne, 1998
1990	Scheduled	Wuebbles, *et al.*, 1993 Baughcum, *et al.*, 1994 Baughcum, *et al.*, 1996a
	Charter, military, general aviation, former USSR/China	Wuebbles, *et al.*, 1993 Landau, *et al.*, 1994
1992	Scheduled	Baughcum, *et al.*, 1996a
	Charter, military, general aviation, former USSR/China	Metwally, 1995 Mortlock and Van Alstyne, 1998
2015	Scheduled	Wuebbles, *et al.*, 1993 Baughcum, *et al.*, 1994 Baughcum and Henderson, 1995 This work
	Charter, military, general aviation, former USSR/China	Wuebbles, *et al.*, 1993 Landau, *et al.*, 1994 Mortlock and Van Alstyne, 1998

The work described in this report was conducted under NASA Langley Research Center Contract NAS1-20267, Task 5. The NASA Langley Task Manager was Donald L. Maiden.

The principal investigator of the work was Steven L. Baughcum. Stephen C. Henderson and Terry Higman generated the projected aircraft departure data based on projections of passenger demand from the Boeing Current Market Outlook. Rebel R. Nichols, Douglas P. DuBois, and Donald J. Sutkus provided the performance and emissions technology projections. Donald J. Sutkus collected the data and calculated the 3-dimensional aircraft emission inventories using the Boeing Global Aircraft Emissions Code (GAEC). The analysis of the results was completed by Steven L. Baughcum.

2.0 Methodology

2.1 Overview

Figure 2-1 shows a schematic of the general process that was used to develop the NASA 2015 global aircraft emissions inventory for the scheduled aircraft fleet. Projections of the aircraft/engine combinations that would most likely be in existence in 2015 were made. Then, based on regional aircraft demand growth projections from the Boeing Current Market Outlook (CMO) (Boeing Commercial Airplane Group, 1996), a scheduled aircraft fleet route schedule was developed for the year 2015. Performance and emission characteristics were assigned to each aircraft/engine combination projected to be in the 2015 scheduled aircraft fleet based on aircraft and aircraft engine market and technology projections. These were used along with the 2015 route schedule to project the global scheduled aircraft fleet fuel burn and emissions for the year 2015. The details of the process outlined in Figure 2-1 are given in the subsections which follow.

2.2 Market Forecasting

2.2.1 Air Traffic Growth

Based on past market trends, growth in air travel seems to be determined by two effects. The first effect is economic growth, measured as an increase in Gross Domestic Product (GDP), which explains about two-thirds of total air travel growth. The second effect is the increased value created by air travel, as airlines reduce fares and increase services. Over time, this second effect will cause the share of GDP that is spent on air travel to increase.

The world GDP is expected to grow by 3.4% per year over the next ten years (Boeing Commercial Airplane Group, 1996). This growth rate is a composite of the relatively low growth rates in the mature economies and the very high rates in the newly industrialized countries. Rates for all economies will decline somewhat between 2005 and 2015 as populations age and the economies of the now newly industrialized countries become more mature.

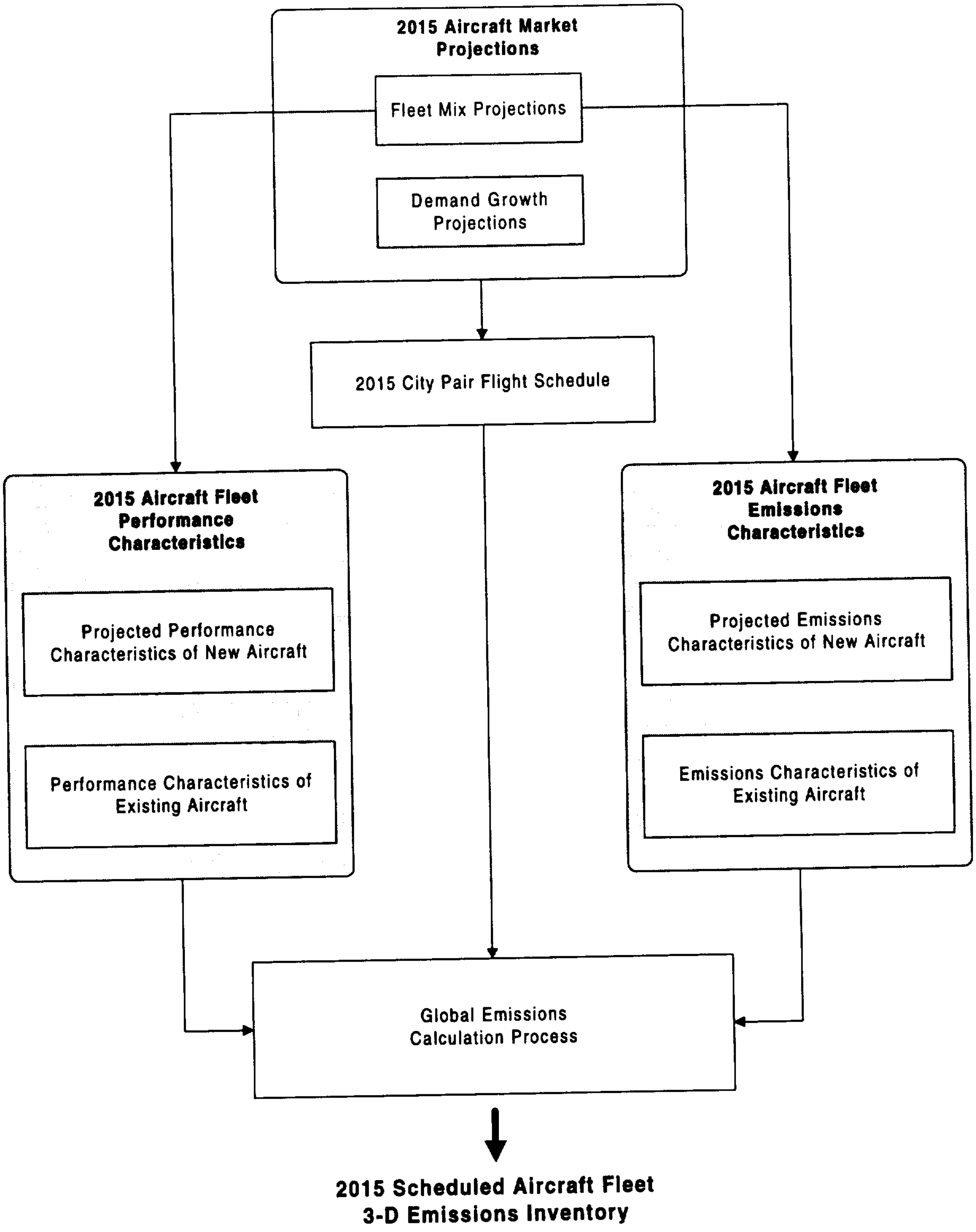

Figure 2-1. Schematic of the process for projecting 2015 scheduled aircraft fleet global emissions and fuel burn.

Since the growth in air travel reflects the growth in GDP, air travel growth rates vary considerably by country and region. Growth rates also reflect the changes that are being made in the political dimensions of air travel. Reduction in regulations governing market access and fares will powerfully affect the value that aviation is allowed to provide. Worldwide demand for air travel is expected to average around 5% per year growth for the next twenty years, with international travel growing at a slightly faster rate than domestic travel (Figure 2-2). By 2015, demand for air travel will be 3.1 times greater than in 1992 (Figure 2-3). Appendix A shows the air travel demand history and forecast (in billions of revenue passenger miles) for 12 domestic and 33 international traffic flows.

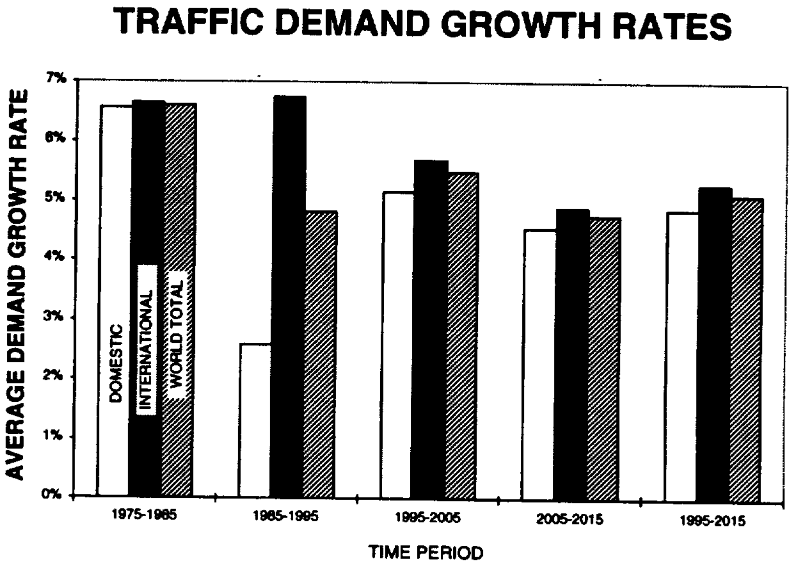

Figure 2-2. Traffic demand growth rates from 1975 through 2015.

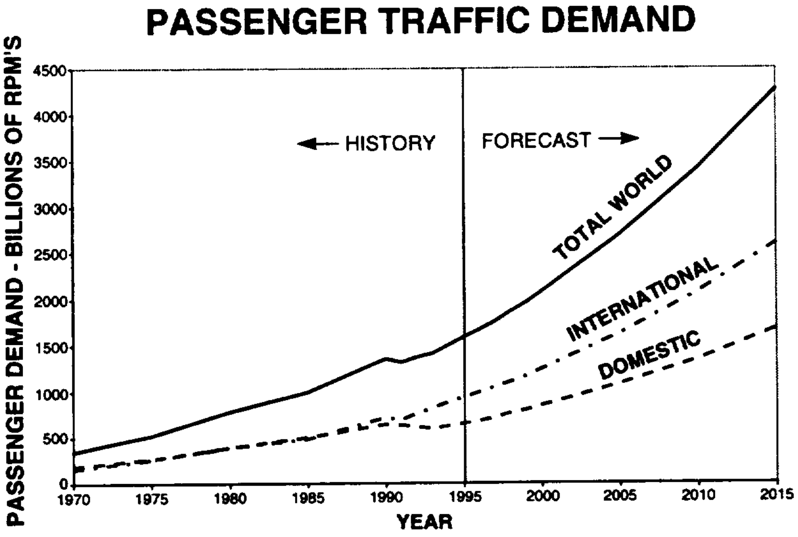

Figure 2-3. Past and projected scheduled aircraft fleet passenger traffic demand.

2.2.2 Fleet Projections for the Year 2015

The total projected demand for air travel in the year 2015 must be assigned to actual aircraft and routes in order to create a three-dimensional emissions inventory. For the purpose of forecasting large turbojet airplane requirements, the 45 flows of Appendix A were consolidated into 22 major regional traffic flows and a detailed forecast of the fleet requirements of the airlines in each region was created, using consolidated growth rates and a projected city-pair schedule derived from the schedules for 1995 published in the Official Airline Guide (OAG) a publication of the Reed Travel Group (Oakbrook, IL). Individual city-pair service schedules for 1995 within each of the 22 traffic flow regions were grown to 2015 by the consolidated regional growth rate applicable for that region. Airplane types were assigned to routes using a market share forecast model. These proprietary market share forecast methods take into account the market "fit" of each airplane type on each city-pair, assigning airplane types according to the total demand, forecast split between increasing frequency and increasing airplane size, city-pair range, and historical fleet trends of airlines serving the particular market.

The turboprop market (for which we do not create a detailed forecast) was projected for 2015 assuming that city-pairs not served by the smallest turbojet category (50-90 seats) after demand growth to 2015 will continue to be served by small, medium, or large turboprops.

The result of the fleet assignment task is a detailed city-pair flight schedule by airplane type required to satisfy the forecast scheduled passenger demand in 2015. This is the schedule used to calculate the 3-dimensional emissions inventory for scheduled passenger service.

Table 2-1 below shows the distribution by airplane category of the 1995 fleet and of the forecast 2015 fleet, including airplanes removed and added to each category over the 1995 to 2015 time period.

Table 2-2 lists the 110 specific aircraft/engine combinations that were used in this study to represent the 2015 scheduled aircraft fleet. The Airbus A3XX was not included as a separate aircraft/engine combination in the 2015 fleet projection. Instead, all A3XX traffic projected for 2015 was assigned to 747-500/600/800 models for which predicted performance data was available.

Table 2-1. Distribution by airplane category of the 1995 fleet and the forecast 2015 fleet.

Airplane Category	General Airplane Types	Year-End 1995 Units	Units Removed 1995-2015	Units Added 1995-2015	Year-End 2015 Units
50-90 seats	F28 F70 Bae 146/RJ70/RJ85 BAC 1-11 DC-9-10 Canadair RJ	617	171	1329	1,775
91-120 seats	717-200 727-100 737-100/-200/-500/-600 DC-9 MD-87 F 100 RJ100 Caravelle Concorde	2,664	764	1677	3,577
121-170 seats	737-300/-400/-700/-800 727-200 720 A319 A320 Trident-3 Mercure MD-81/-82/-83/-88 MD-90 DC-8-10/20	3,835	1818	5004	7,021
171-240 seats	757-200/-300 707-300B/C A321 DC-8-30/-40/-50/-60/-70	1,095	106	2834	3,823
241-400 seats	767 777-200/-300 A300 A310 A330 A340 L-1011 DC-10 MD-11	1,913	491	3473	4,895
>400 seats	747 777-300 747-X A3XX	942	540	1588	1,990
Totals		**11,066**	**3890**	**15905**	**23,081**

Table 2-2. Aircraft/engine combinations projected to be in the 2015 scheduled aircraft fleet

Aircraft	Engine	Aircraft	Engine	Aircraft	Engine
*717-200	BR-715	767-200	CF6-80A2	A330-200	CF680E1A4
727-100F	JT8D-7	767-200	JT9D-7R4D	*A330-200	PW4168
727-200	JT8D-15	767-200E	CF6-80A2	*A330-200	TRENT 772
727-200F	JT8D-15	767-200E	JT9D-7R4D	A330-300	CF680E1A2
727-200F	JT8D-15	767-300	JT9D-7R4D	A330-300	PW4168
727-200F	TAY650	767-300	CF6-80A2	A330-300	TRENT772
737-200	JT8D-15	767-300E	RB211524	A340-200	CFM56-5C
737-200	JT8D-15	767-300E	CF6-80C2	A340-300	CFM56-5C
737-200F	JT8D-15	767-300E	PW4060	A340F	CFM56-5C
737-300	CFM56-3	767-300F	CF6-80A2	BAE146	LF502
737-300F	CFM56-3	777-200	PW4077	BAE146F	LF502
737-400	CFM56-3C	777-200	TRENT877	CRJ	CF34-3A1
737-500	CFM56-3C	777-200	GE9076B	DC-8-71F	CFM56-3
*737-600	CFM56-7	777-200E	TRENT877	DC10-10	CF6-6D
*737-700	CFM56-7	777-200E	GE90-90B	DC10-10F	CF6-6D
*737-800	CFM56-7	777-200E	GE9085B	DC10-30	CF6-50C2
747-200	JT9D-7J	777-200E	PW4084	DC10-30F	CF6-50C2
747-200F	JT9D-7J	777-200F	PW4077	DC9-30	JT8D-7
747-300	CF680C2B1	*777-300	PW4090	DC9-30HKF	JT8D-7
747-400	PW4056	*777-300	TRENT877	DC950	JT8D-15
747-400	CF680C2	*777-300	GE9085B	F-70	TAY-650
747-400	RB211524G	A300-600	CF6-80C2	F10-100	TAY-650
747-400F	PW4056	A300-600	PW4158	IL96-300	PW2337
*747-500	PWGEJV	A300-B4	CF6-50C2	L-1011F	RB211524B
*747-500	TRENTXX	A300F	CF6-50C2	LGTURB	PW125
*747-600	PWGEJV	A310-200	CF6-80A3	MD-11	PW4460
*747-600	TRENTXX	A310-200	JT9D-7R4E	MD-11	CF680C2
*747-600X	PWGEJV	A310-200F	CF6-80A3	MD-11F	CF680C2
*747-600X	TRENTXX	A319	V2500	MD-82	JT8D-217A
*747-800X	TRENTXX	A319	CFM56-5A	MD-82F	JT8D-217A
*747-800X	PWGEJV	A320-200	V2500	MD-90	V2500
757-200	RB211535	A320-200	CFM56-5A1	MDTURB	PW120
757-200	PW2040	A320-200F	CFM56-5A1	RJ-100	LF-507
757-200ER	PW2040	A321	CFM56-5	RJ-70	LF-507
757-200F	PW2040	A321	V2500	RJ-85	LF-507
*757-300	RB211535	*A322	CFM56-5	SMTURB	PT6A
*757-300	PW2040	*A322	V2500		

*aircraft/engine combinations not in production before or at the time of this study

2.3 Technology Projections

2.3.1 Aircraft Performance

For purposes of this study, it was assumed that in the future, as in the past, major new airframe technologies affecting aircraft performance will be introduced to the fleet through new aircraft models and that once a particular aircraft model is introduced to the fleet, its performance characteristics will not change significantly with time due to airframe and engine modifications. Based on this assumption, unmodified, currently available performance data were used to model the performance characteristics of aircraft/engine combinations in 2015 that were already in production at the time this study was conducted.

Projected performance data obtained by building on the performance characteristics of current production aircraft was used to model aircraft/engine combinations in the 2015 fleet that were not in production before or at the time of this study. Aircraft/engine combinations for which projected performance data was used are denoted by asterisks placed next to the airframe in Table 2-1.

2.3.2 Aircraft Engine Emissions Characteristics

In general, the engine models projected to be in the 2015 scheduled fleet represented the state of the art engine technology available at the time the projections were made. Aggressive projections of the penetration of low emissions engine designs were used when assigning emissions characteristics to aircraft/engine combinations. Cargo aircraft that were converted from passenger aircraft were exceptions to this general rule.

All of the emissions engines assigned to aircraft in the projected 2015 fleet for this study were either in production or under the final stages of development at the time the assignments were made. Cost, maintenance of airline fleet commonality and likely market and political forces that would drive the introduction of new engine technology into the fleet were some of the factors considered when assigning specific emissions engines to the aircraft/engine combinations.

At the time technology projections for this study were being made, a number of low emissions derivatives of previously existing engines had recently entered production or were in the final stages of development. Some of these derivatives were designed to target HC and CO for reduction while others were designed to target NOx. Some will be introduced into the global aircraft fleet through normal maintenance overhauls or retrofitting while others will require the complete re-engining of an aircraft in order for them to be introduced.

In the cases where a low emissions derivative version of an engine was available or would be in the foreseeable future, a projection was made of its most likely market penetration into the 2015 fleet for each affected aircraft/engine combination. If the low emissions derivative engine was projected to be on the majority of aircraft represented by a particular aircraft/engine combination, it was assigned to that aircraft/engine combination. If not, the standard engine was assigned.

Currently, research and development work is being done under such programs as the European BRITE/EURAM program and the NASA Advanced Subsonic Technology (AST) program to develop advanced subsonic aircraft engines that will be more fuel efficient and have better emissions characteristics than the best aircraft engines currently in production. The goal of the NASA AST program for example, is to promote the development of technology that will lead to aircraft engine designs that will be 8-10% more fuel efficient than current production engines and will have landing take-off cycle NOx emissions that will be 70% below the ICAO CAEP2 limit. The BRITE/EURAM program has similar goals.

By 2015, some percentage of the scheduled aircraft fleet will likely have engines that utilize technologies currently being developed to meet the goals of the NASA and European advanced engine technology programs. It was assumed when making projections for 2015 that penetration of such technologies into the 2015 scheduled fleet will be minimal. Several factors must be taken into account when trying to project this technology penetration. These include the time it will take to bring demonstrated technology to production worthiness, along with available opportunities for introduction via new airplane types/derivatives.

The combined effects of the 2015 marketing and technology projections on the NOx technology level of the projected 2015 fleet can be seen in Figure 2-4. For the 1992 and 2015 scheduled aircraft fleets, Figure 2-4 shows the fraction of the total global fuel burned by aircraft having landing take-off (LTO) cycle NOx emissions at a given level relative to the ICAO CAEP/2 NOx standard. The ICAO CAEP/2 NOx standard specifies the amount of NOx emissions that may be created by an engine during a standard LTO cycle where it is run at specified power settings for specified amounts of time to simulate the taxi, takeoff, climbout and approach segments of a typical mission. The CAEP/2 NOx standard and LTO cycle are discussed in more detail elsewhere (ICAO, 1993).

Even though the LTO cycle emissions performance of an aircraft engine may not be directly linked to its emissions performance over an entire flight, it is still useful as a general indicator of the emissions technology level of the engine. The LTO NOx technology distribution for the 1992 fleet shown in Figure 2-4 is bimodal in shape with peaks occurring in the 10 to 20 percent and -10 to -20 percent categories. The peak in the 10 to 20 percent category is due to the older technology aircraft present in the 1992 fleet while the newer technology aircraft in the fleet are represented by the peak in the -10 to -20 percent category.

The effect on the 2015 fleet of the retirement of old technology engines and the introduction of new low emissions technology engines can be seen by the drastically reduced number of aircraft in the 2015 forecast fleet having LTO NOx emissions that are above the CAEP/2 limit and the shift in the fuel burn distribution of those aircraft having LTO NOx emissions that are below the CAEP/2 limit further to the left.

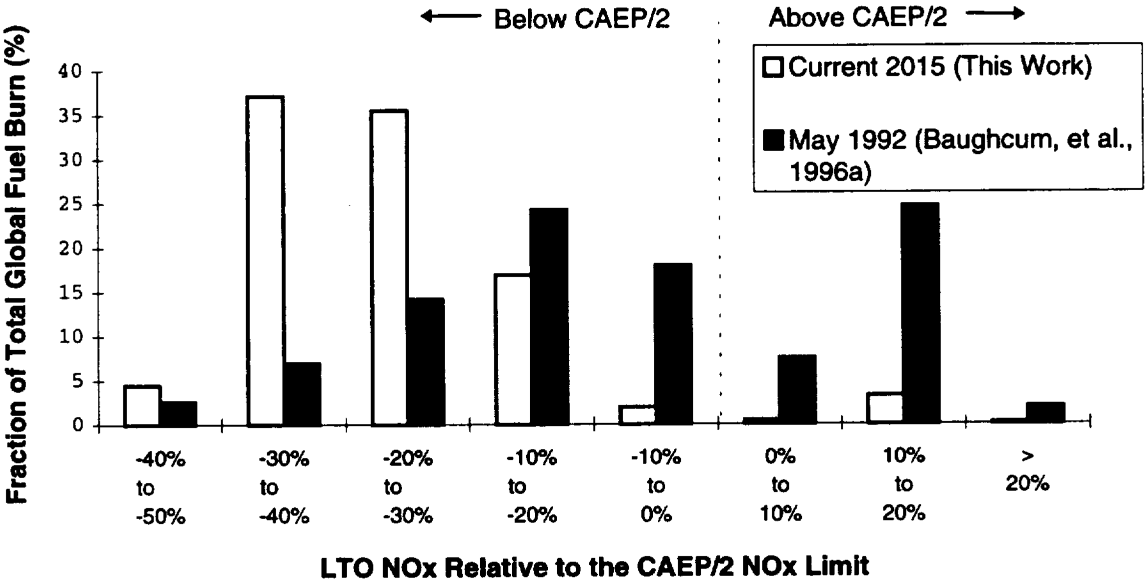

Figure 2-4. Fraction of total global fuel burned by aircraft having LTO NOx emissions at a given level relative to the CAEP/2 NOx limit for 1992 (Baughcum *et al.*,1996a) and 2015 (current study).

2.4 Calculation of Global Emissions

2.4.1 Airplane/Engine Performance Data Substitution

Boeing has performance data needed to calculate fuel burn and emissions for a large number of turbojet and turbofan powered airplane types. Actual performance data based on flight tests was available for all Boeing models that were in production in 1997 and predicted performance data based on competitive analysis was available for most non-Boeing models.

For a small number of the aircraft/engine combinations projected to be in the 2015 fleet, no actual or predicted performance data was available. In most of these cases, available performance data for aircraft having similar characteristics were used to model the performance characteristics of these aircraft/engine combinations. For example performance data for the BAE146-300 with ALF502R-5 engines was used to model the RJ-100 with LF-507 engines. This substitution was appropriate because the RJ-100 was developed from the BAE146-300 and the engines powering both of these aircraft have similar thrust ratings.

The Canadair Regional Jet (CRJ) and the IL96-300 were the only aircraft/engine combinations for which there was no performance data available in the Boeing database that could be used as a direct substitute. A best attempt was made to model the performance characteristics of these aircraft based on what was known about their general performance characteristics.

It was assumed that freighter aircraft projected to be in the 2015 scheduled aircraft fleet would operate at a 70% cargo load factor. To account for the increased take-off gross weight associated with freighter versions of passenger aircraft, performance characteristics of freighter aircraft with a 70% cargo load factor were modeled using passenger versions loaded to 70% of maximum structural loading. Take off gross weights for large freighter aircraft were on average 12% to 20% higher than those of their passenger counterparts.

As in previous NASA global emissions inventory studies, for purposes of modeling performance and emissions, all turboprop models were grouped into three categories, small, medium and large. The "small" category includes airplanes such as the DeHaviland Twin Otter, the "medium" category includes airplanes such as the DeHaviland Dash-8, the "large" category includes airplanes such as the Fokker F-27 and F-50. No improvements in the emissions or performance characteristics of the turboprop aircraft over the 1992 technology level were assumed in this study i.e. the same performance and emissions files used to model turboprop aircraft in the 1992 NASA work (Baughcum, *et al.* 1996a) were used in the current study.

2.4.2 Mission Performance Calculations

The airplane performance data files used to represent the performance characteristics of the airplane/engine combinations shown in Table 2-1 provide time, fuel burned and distance flown as a function of aircraft gross weight and altitude for climbout, climb, and descent conditions. They also provide tables of fuel mileage (nautical miles per pound of fuel burned) as a function of gross weight, Mach number and altitude for cruise conditions. These performance data files were generated using the proprietary Boeing Mission Analysis Program (BMAP), and each file covered the whole operating envelope of the airplane. This allowed simple interpolation routines to be used by the Global Atmospheric Emissions Code (GAEC), a proprietary program created for these calculation tasks.

The following assumptions were made when producing the aerodynamic performance files that were used in this study:

- No winds
- No cargo for passenger aircraft (payload = passengers + baggage)
- No fuel tankering
- International Standard Atmosphere (ISA) temperatures
- Westward cruising altitudes
- Fuel density of 6.75 lb/gallon
- Fuel energy content of 18,580 BTU/lb
- Sea level runways with no weight or runway restrictions
- Passenger weights ranging from 200 to 210 lbs depending on aircraft seating arrangements
- 70% load factor for passenger aircraft
- 70% maximum structural weight for freighter aircraft loading
- Typical Boeing mission rules and reserves
- Boeing typical weight calculations used for operating empty weight, maximum landing weight, maximum zero fuel weight etc.
- Direct point to point flight paths (no air traffic control diversions or airport traffic patterns)

Airplane operating weights and passenger counts were obtained primarily from the Boeing marketing database. For some non-Boeing and future aircraft derivatives, performance data was estimated by extrapolating from available aircraft performance data.

2.4.3 Calculation Methodology

The primary emissions produced by the combustion of jet fuel are water vapor (H_2O) and carbon dioxide (CO_2). The emission indices for these species are determined by the fraction of hydrogen and carbon contained in the fuel. The fractional amount of hydrogen and carbon in commercial aviation fuel is not likely to change significantly by 2015 so emissions indices for carbon dioxide and water were assumed to be the same as those used in previous NASA emissions inventory studies (Baughcum *et al.* 1996a).

Emissions of sulfur dioxide (SO_2) from aircraft engines are determined by the levels of sulfur compounds in the jet fuel. Although jet fuel specifications require sulfur levels below 0.3 wt.%, current sulfur levels are typically much lower than this. A world-wide survey of aviation fuel sulfur content made by Boeing in 1989 gave an average sulfur content of 0.042 weight percent with 90% of the samples below 0.1 wt.% (Hadaller and Momenthy, 1989). Aviation fuel sulfur levels are projected to drop to about 0.02 wt.% by 2015 (Hadaller and Momenthy, 1993). This would bring the average sulfur EI down to 0.4 from the value of 0.8 that was assumed for the 1992 scheduled aircraft fleet (Baughcum *et al.*, 1996a).

Emission indices for the year 2015 for CO_2, H_2O and SO_2 (in units of grams of emissions per kilogram of fuel burned) based on the analyses of Hadaller and Momenthy for commercial Jet A fuel are given below in table 2-3.

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

Emission	Emission Index
Carbon Dioxide (CO_2)	3155
Water (H_2O)	1237
Sulfur oxides (as SO_2)	0.4

Nitrogen oxides (NO_x), carbon monoxide (CO) and hydrocarbons (HC) are produced in the aircraft engine within the combustor and vary in quantity according to the combustor conditions. Nitrogen oxides are produced in the high temperature regions of the combustor primarily through the oxidation of atmospheric nitrogen. Thus, the NO_x produced by an aircraft engine is sensitive to the pressure, temperature, flow rate, and geometry of 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 within the combustor is relatively low and combustion is less efficient.

The emissions are characterized in terms of an emission index in units of grams of emission per kilogram of fuel burned. Nitrogen oxides consist of both nitric oxide (NO) and nitrogen dioxide (NO_2). For NO_X, the emission index [EI(NO_X)] is given as gram equivalent NO_2 to avoid ambiguity. Although hydrocarbon measurements of aircraft emissions by species have been made (Spicer *et al.,* 1992), only total hydrocarbon emissions are considered in this work, with the hydrocarbon emission index [EI(HC)] given as equivalent methane (CH_4).

For the majority of the engines considered in this study, emissions data from engine certification measurements were used (ICAO, 1995; ICAO/CAEP, 1995, 1998) In these measurements, emissions of nitrogen oxides (NOx), carbon monoxide (CO) and total hydrocarbons (HC) are measured at standard day sea level conditions at four power settings [7% (idle), 30% (approach), 85% (climbout) and 100% (takeoff)]. No official ICAO certification data was available for some of the engines that were projected to be in the 2015 scheduled aircraft fleet because they were still in various stages of development or the data had not yet been officially submitted to the ICAO databank at the time the 2015 projections were made. In these cases, the most accurate possible emissions data was requested directly from the engine manufacturer. For engines that had not yet undergone certification testing, proprietary emissions data based on preliminary engine tests or emissions predictions developed from existing engine cycles was provided by the engine manufacturer. Because data for turboprop engines is not given in the ICAO Engine Emissions Databank, emissions data obtained directly from the engine manufacturers was used for the three sizes of turboprops considered in this study.

All global emissions calculations were done using the Global Atmospheric Emissions Code (GAEC) as described previously (Baughcum, *et al.*, 1996a). Performance data and engine emissions data were matched to each airplane/engine combination projected to be in the 2015 scheduled aircraft fleet based on the technology projections discussed in section 2.3 of this report. The Boeing Fuel Flow Method #2 was used by GAEC to calculate emissions at actual flight conditions for all of the aircraft/engine routes given in the 2015 projected route schedule using this performance and emissions data. Boeing Fuel Flow Method #2 correlates emission indices measured during engine certification tests with fuel flow calculated from performance data and then scales for flight condition temperature, pressure, Mach number and humidity to calculate aircraft emissions corresponding to a particular flight condition. The CAEP Working Group 3 has recommended the adoption of Boeing Method 2 as a standard method for environmental assessments. [Combined Report of the Certification and Technology Subgroups, Paper WG3/WP2, presented by the Chairman of

TSG at the third Meeting of ICAO/CAEP Working Group 3, Bonn Germany, June 1995.]

For purposes of the emissions calculations, the earth's atmosphere was divided into a three dimensional grid of cells with dimensions of 1 degree of latitude by 1 degree of longitude by 1 kilometer in altitude, up to 22 kilometers. Emissions calculated using Boeing Fuel Flow Method #2 for each of the aircraft/engine routes in the 2015 projected route schedule were distributed into the appropriate atmospheric cells by assuming each aircraft/engine flew between city pairs using a great circle route.

3.0 Results and Discussion

3.1 Overview of Results

The global total fuel burn and emissions projected for the year 2015 in the current study are summarized in Table 3-1. For comparison, the results of earlier NASA studies discussed in Section 1 of this report are also included in Table 3-1. The new result is approximately 3.9% lower in fuel burned than the most recent update (Baughcum and Henderson, 1995) but predicts 46% more NOx. Emissions of hydrocarbons are also projected to be larger while carbon monoxide emissions are about the same. Table 3-2 tabulates the globally averaged effective emission indices which highlight the different technology assumptions between the current study and the earlier ones. The reasons for these differences will be discussed in section 3.4.

Compared to the previously published emissions for 1992 scheduled air traffic (Baughcum, *et al.*, 1996a), this scenario predicts an increase in global jet fuel consumption by a factor of 2.6 and an increase in fleet NOx emissions by a factor of 2.9. Total hydrocarbon emissions are predicted to decrease by approximately 11%, while carbon monoxide emissions are projected to increase by a factor of 2.3 relative to 1992. Effective global emission indices (integrated over latitude, longitude, and altitude) are projected to increase by 8.5%, decrease by 67%, and decrease by 15% for EI(NOx), EI(HC), and EI(CO), respectively.

The decrease in EI(HC) and EI(CO) between 1992 and 2015 is due to the increase in average engine pressure ratio that is projected to occur throughout the fleet because of the retirement of old lower pressure ratio engines and the increased penetration of more efficient engines having higher pressure ratios. The combustor temperatures and pressures in higher pressure ratio engines are greater which leads to more efficient combustion and a reduction in hydrocarbon and CO emissions. Unfortunately, the same combustor conditions that improve combustion efficiency tend to promote the formation of NOx. Thus, the fleet average EI(NOx) in 2015 is projected to increase relative to that of 1992.

The increase in EI(NOx) for the 2015 fleet is in apparent contradiction with Figure 2-4 which shows a shift to lower landing take-off (LTO) cycle NOx levels relative to the CAEP/2 NOx limit from 1992 to 2015. This apparent contradiction can be explained by the fact that the LTO NOx emissions from an engine allowed under the CAEP/2 NOx limit are directly proportional to the pressure ratio of the engine. Therefore, more efficient higher pressure ratio engines may produce larger amounts of NOx in the LTO cycle but remain at or below the same level relative to the CAEP/2 NOx limit.

Table 3-1. Summary of calculated global fuel use and emissions for scheduled air traffic projected for 2015 and comparison with previous study results. (Units = million kg/day).

Traffic Year	Reference	Fuel	NOx	HC	CO
2015	This work	684	9.67	0.47	3.06
2015	Baughcum and Henderson, 1995	712	6.61	0.30	3.19
2015	Baughcum, *et al.*, 1994	697	6.39	0.28	3.12
1992	Baughcum, *et al.*, 1996a	259	3.37	0.53	1.36

Table 3-2. Summary of the globally averaged effective emission indices for scheduled air traffic projected to 2015 and comparison with previous study results. (units = grams of emissions/kilogram of fuel burned).

Traffic Year	Reference	EI(NOx)	EI(HC)	EI(CO)
2015	This work	14.1	0.7	4.5
2015	Baughcum, *et al.*, 1995	9.3	0.4	4.5
2015	Baughcum, *et al.*, 1994	9.2	0.4	4.5
1992	Baughcum, *et al.*, 1996a	13.0	2.1	5.3

The geographical distribution of the NOx emissions for the projected 2015 scheduled air traffic is shown in Figure 3-1. The top panel shows the emissions as a function of altitude and latitude, while the bottom panel shows the emissions as a function of latitude and longitude. Peak emissions are projected to occur over the United States, Europe, the North Atlantic flight corridor, the North Pacific, and the Far East.

The projected fuel use for 2015 is shown as a function of latitude in Figure 3-2. For comparison, a similar plot for 1992 scheduled air traffic is shown there as well. Most of the air traffic is expected to be in the Northern Hemisphere, primarily at mid-latitudes. Figure 3-3 shows the fraction of the global fuel use occurring within each 1 degree latitude band, illustrating similar distributions to those of 1992.

The distribution of emissions as a function of altitude is shown in Figure 3-4. Peak fuel use and NOx emissions occur at cruise altitudes since most of the flight time occurs at those altitudes. Peak CO and hydrocarbon emissions occur during the landing/takeoff cycle during idle and taxi conditions where power settings are relatively low and the combustor is relatively inefficient.

The effective emission indices (integrated over latitude and longitude) for the scheduled fleet are shown as a function of altitude in Figure 3-5.

The total fuel burned and emissions for the 2015 scheduled fleet as a function of altitude (summed over latitude and longitude) are tabulated in Table 3-3. Table 3-3 also shows the cumulative percentage of total fuel burned and emissions as a function of altitude and the effective emission indices for NOx, HC, and CO.

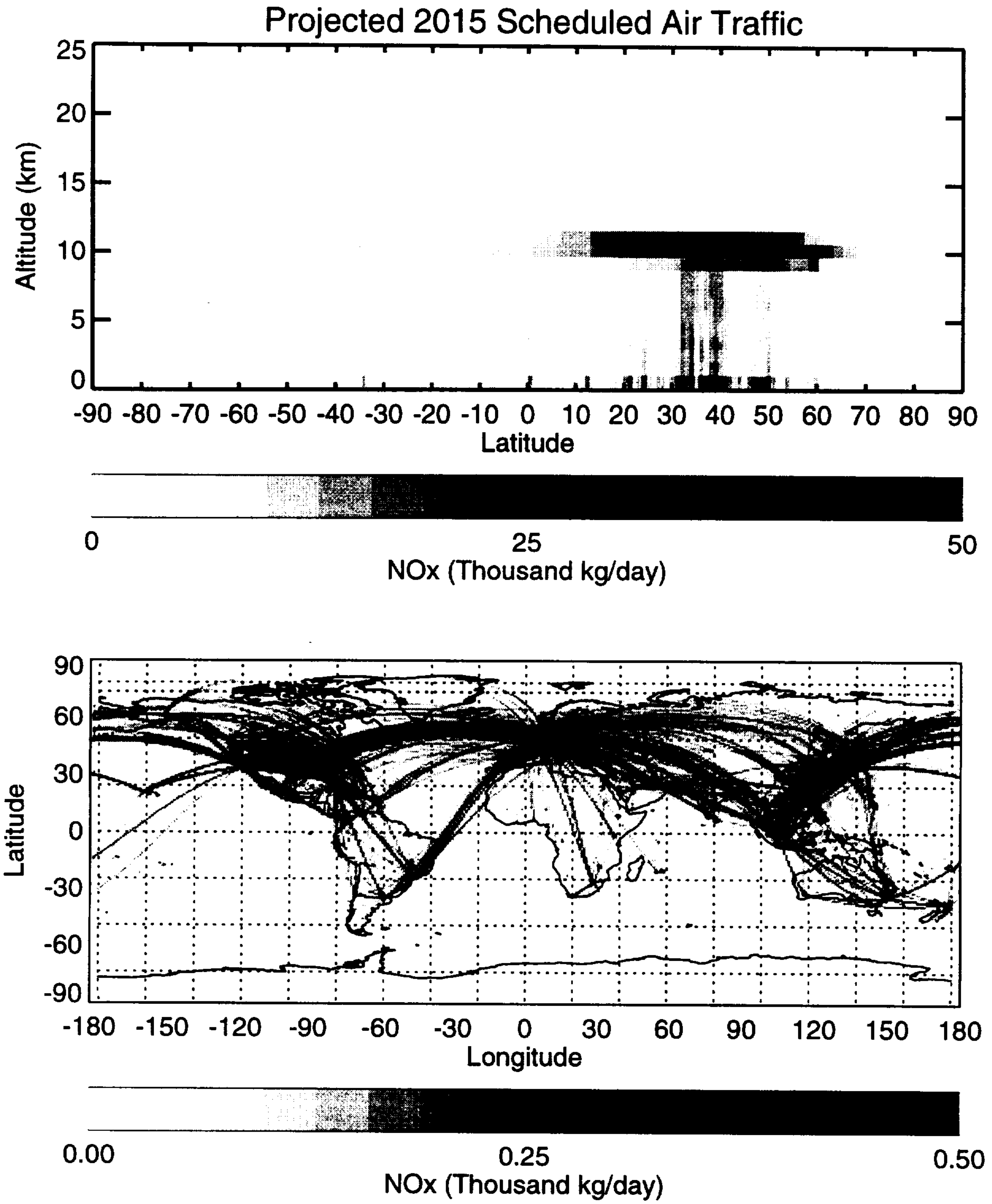

Figure 3-1. NOx emissions for scheduled aircraft, projected to 2015, as a function of altitude and latitude (summed over longitude, top panel) and as a function of latitude and longitude (summed over the 0-15 km altitude band, bottom panel). (Values greater than maximum are plotted as black.)

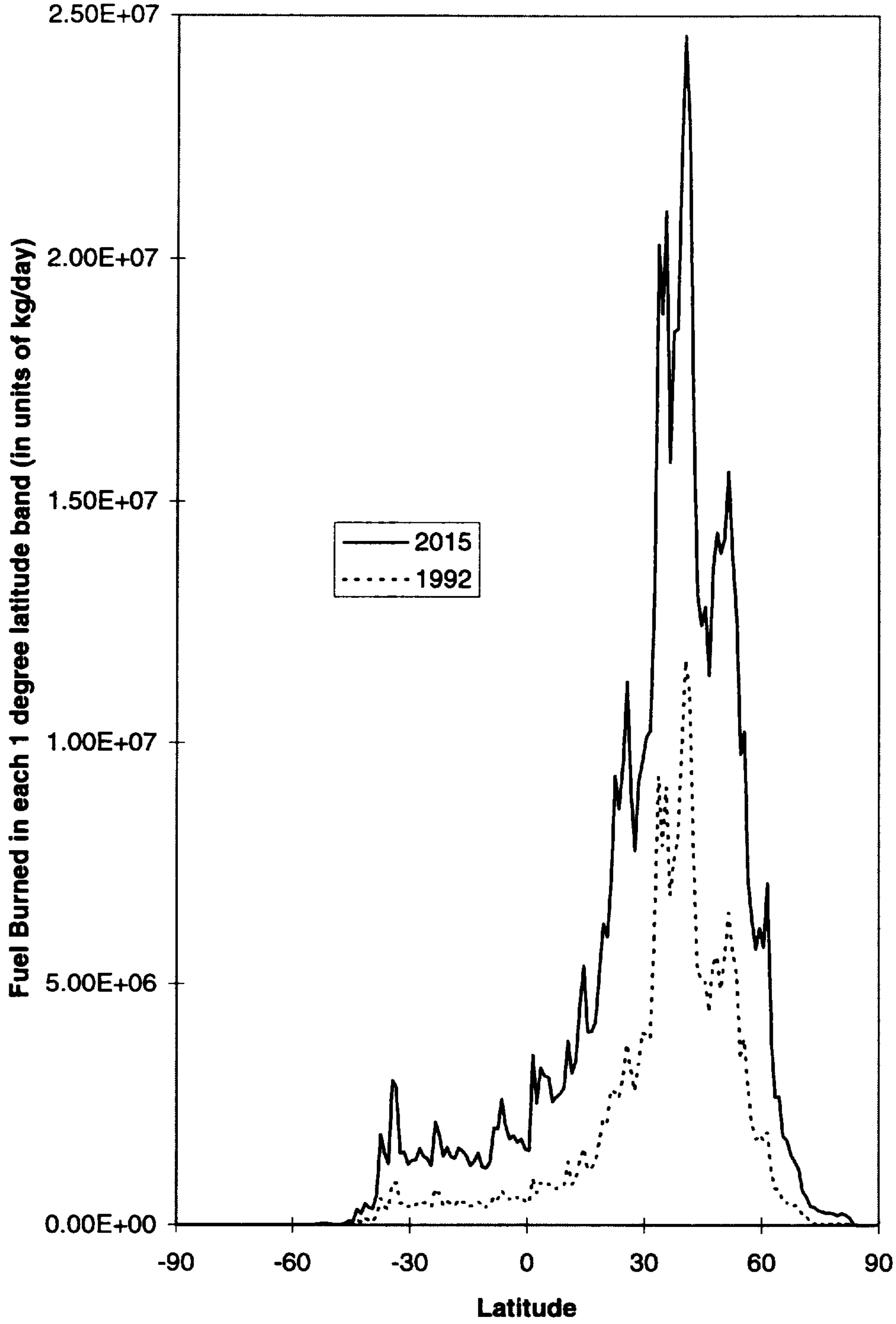

Figure 3-2. Fuel use distribution as a function of latitude, comparing the 2015 projection with that calculated for 1992 for scheduled air traffic.

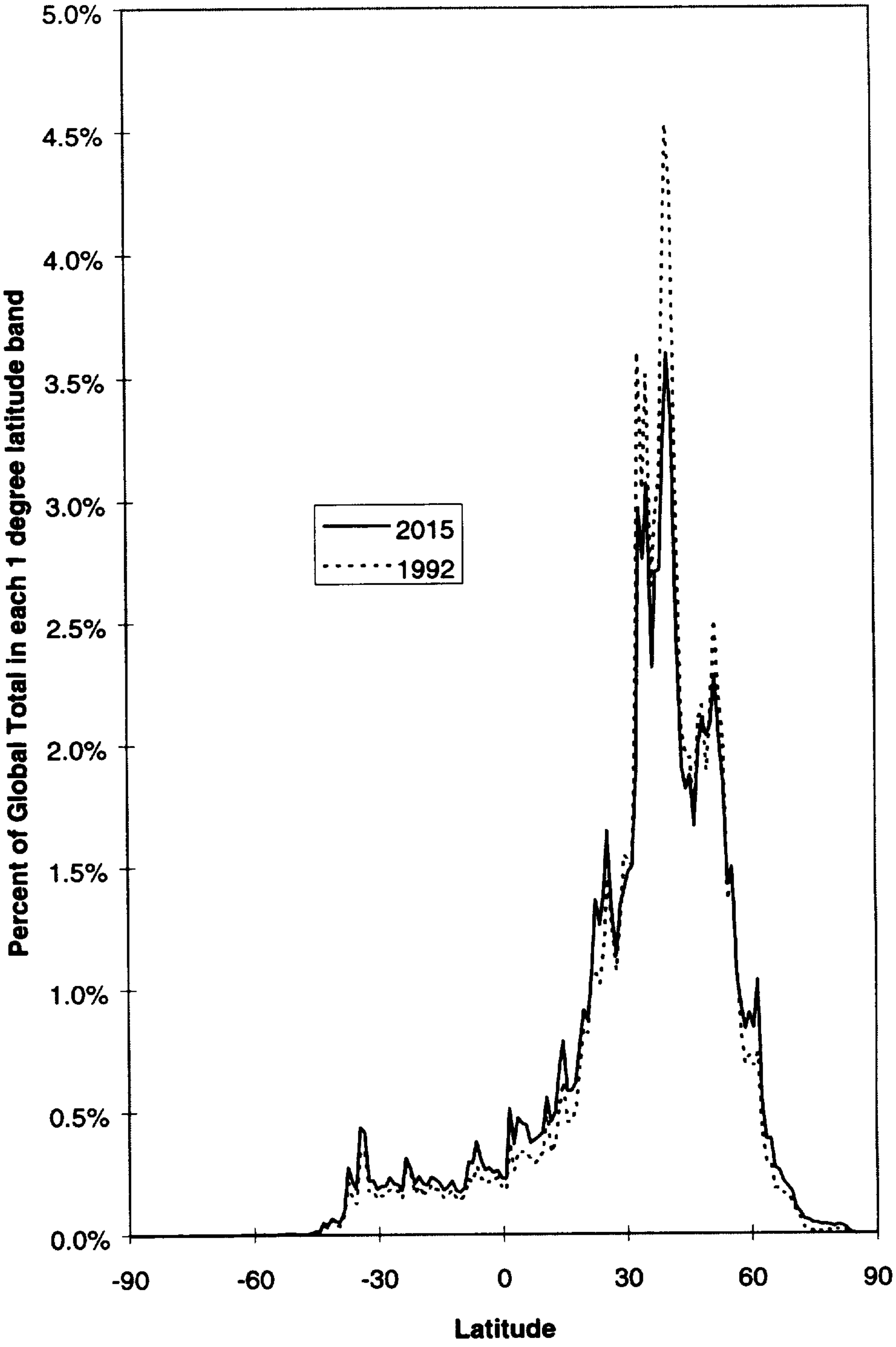

Figure 3-3. Fractional distribution global fuel use as a function of latitude for the 2015 projection and 1992.

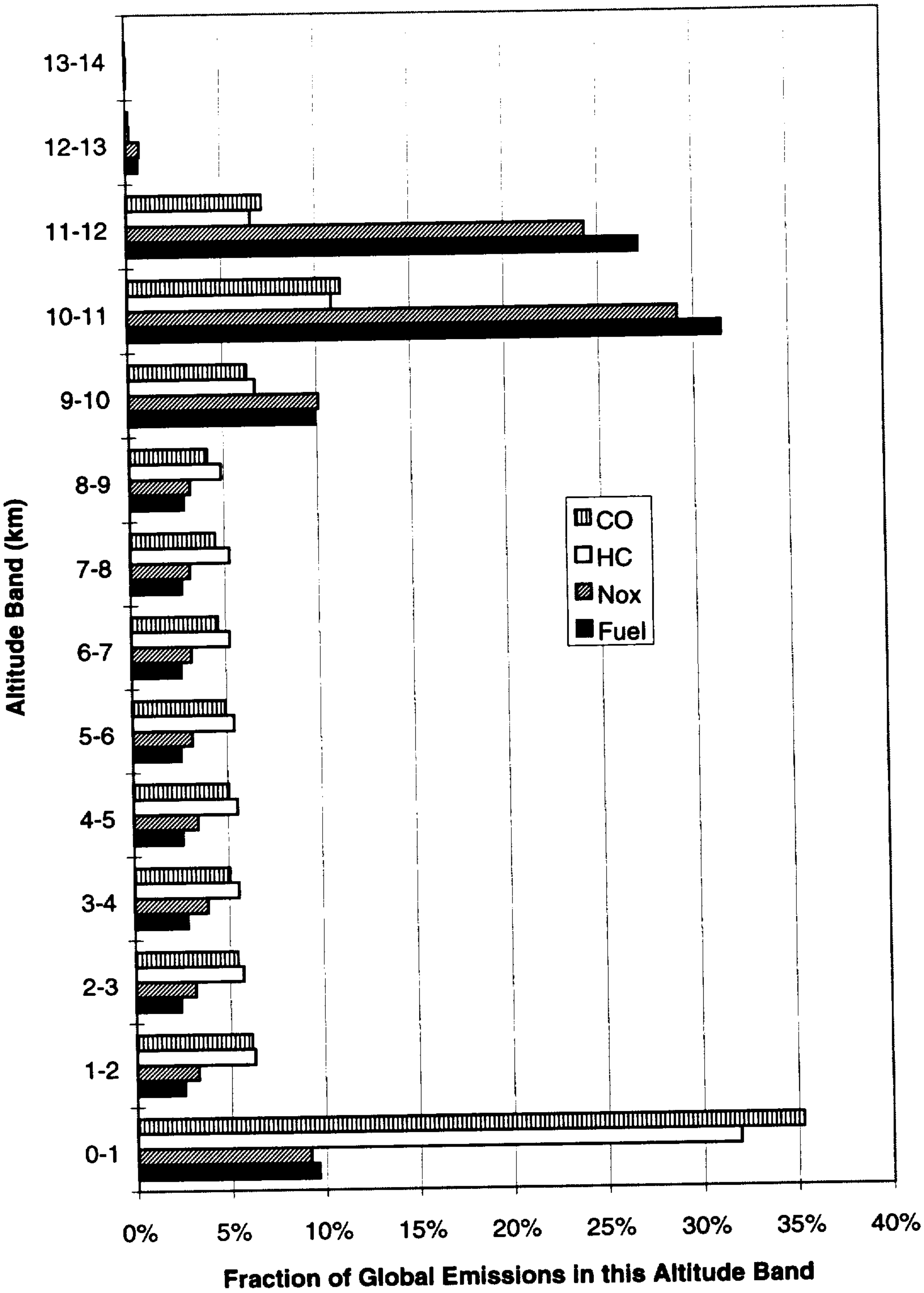

Figure 3-4. Emission distribution as a function of altitude for fuel burned, NOx, hydrocarbons, and CO for the 2015 scheduled fleet. The results are shown as the percent of the global total integrated over latitude and longitude for each emittant.

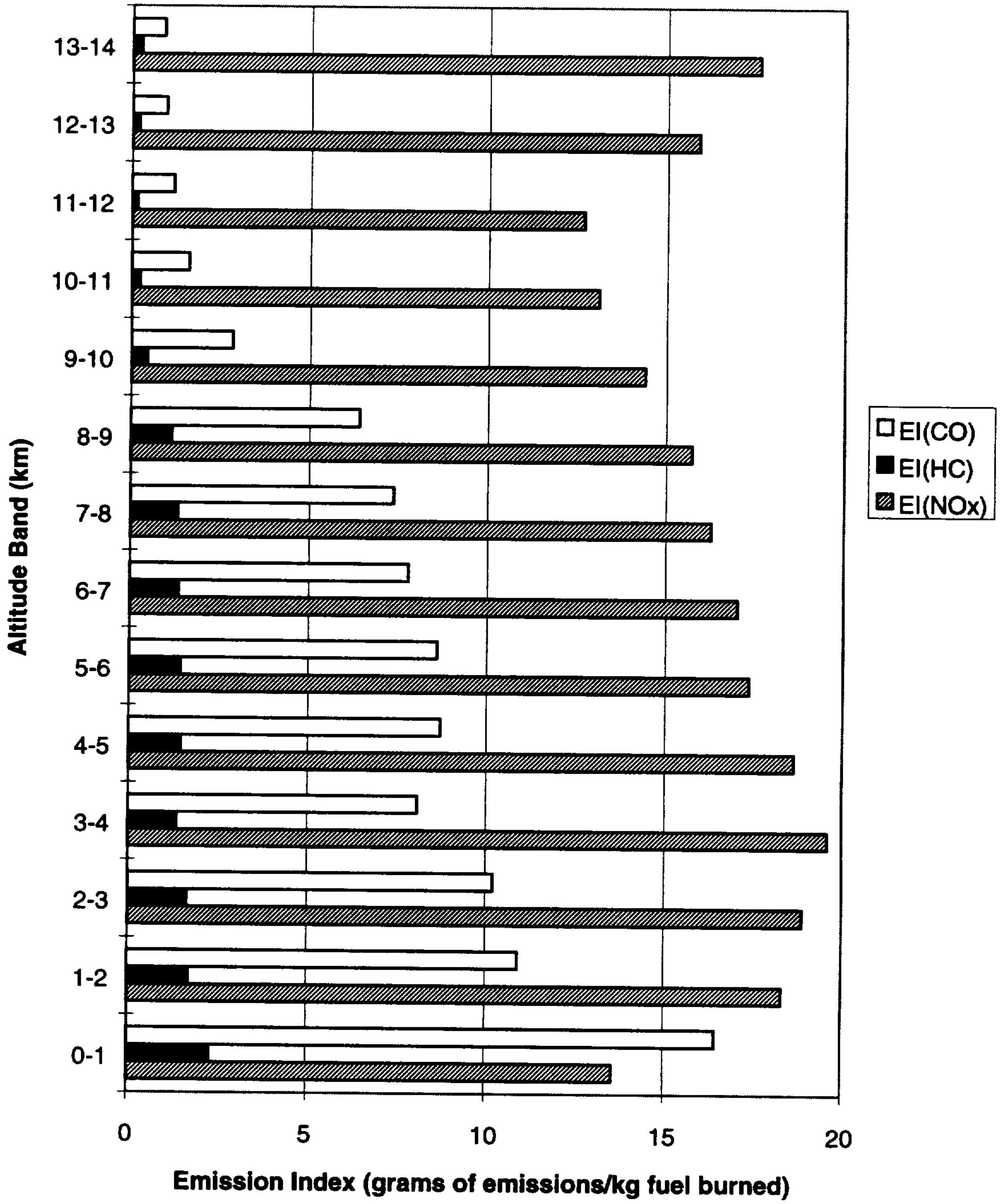

Figure 3-5. Effective emission indices as a function of altitude for the projected 2015 scheduled fleet.

Table 3-3. Fuel Burned, Emissions, Cumulative Fractions of Fuel Burned and Emissions, and Effective Emission Indices as a Function of Altitude (Summed over latitude and longitude) for scheduled air traffic projected to 2015.

Altitude Band (km)	Fuel (kg/day)	Cum. Fuel (%)	NOx (kg/day)	Cum. NOx (%)	HC (kg/day)	Cum. HC (%)	CO (kg/day)	Cum. CO (%)	EI(NOx)	EI(HC)	EI(CO)
0 -1	6.56E+07	9.6%	8.89E+05	9.2%	1.51E+05	32.0%	1.08E+06	35.2%	13.6	2.3	16.4
1 -2	1.72E+07	12.1%	3.16E+05	12.5%	2.96E+04	38.2%	1.88E+05	41.4%	18.3	1.7	10.9
2 -3	1.63E+07	14.5%	3.07E+05	15.6%	2.70E+04	43.9%	1.66E+05	46.8%	18.9	1.7	10.2
3 -4	1.92E+07	17.3%	3.76E+05	19.5%	2.61E+04	49.5%	1.55E+05	51.9%	19.6	1.4	8.1
4 -5	1.78E+07	19.9%	3.31E+05	22.9%	2.60E+04	55.0%	1.55E+05	56.9%	18.6	1.5	8.7
5 -6	1.76E+07	22.5%	3.05E+05	26.1%	2.55E+04	60.4%	1.51E+05	61.9%	17.4	1.4	8.6
6 -7	1.81E+07	25.1%	3.08E+05	29.3%	2.47E+04	65.6%	1.41E+05	66.5%	17.0	1.4	7.8
7 -8	1.87E+07	27.9%	3.05E+05	32.4%	2.49E+04	70.9%	1.38E+05	71.0%	16.3	1.3	7.4
8 -9	1.98E+07	30.7%	3.11E+05	35.6%	2.30E+04	75.7%	1.27E+05	75.1%	15.7	1.2	6.4
9 -10	6.77E+07	40.6%	9.75E+05	45.7%	3.17E+04	82.4%	1.92E+05	81.4%	14.4	0.5	2.8
10 -11	2.15E+08	72.1%	2.82E+06	74.9%	5.10E+04	93.2%	3.46E+05	92.7%	13.1	0.2	1.6
11 -12	1.86E+08	99.3%	2.35E+06	99.2%	3.10E+04	99.8%	2.20E+05	99.9%	12.7	0.2	1.2
12 -13	4.39E+06	99.9%	6.97E+04	99.9%	8.47E+02	100.0%	4.23E+03	100.0%	15.9	0.2	1.0
13 -14	3.80E+05	100.0%	6.69E+03	100.0%	9.94E+01	100.0%	3.42E+02	100.0%	17.6	0.3	0.9
Global Total	**6.84E+08**		**9.68E+06**		**4.72E+05**		**3.06E+06**		14.1	0.7	4.5

3.2 Distribution Between Aircraft Size Categories

The fuel use and emissions projected for 2015 for different airplane sizes is summarized in Table 3-4. The effective global emission indices projected for each of these sizes is tabulated in Table 3-5.

Table 3-4. Summary of global fuel use and emissions for year 2015 air traffic by airplane size category. (Units = million kg/day).

Airplane Size	Fuel	NOx	HC	CO
Turboprop	3.9	0.04	0.002	0.02
50-90 passengers	22.1	0.19	0.035	0.36
91-120 passengers	37.9	0.41	0.051	0.39
121-170 passengers	100.2	1.24	0.070	0.57
171-240 passengers	81.2	1.09	0.043	0.41
241-400 passengers	176.8	2.77	0.112	0.61
> 400 passengers	167.0	2.50	0.047	0.29
Freighter	94.8	1.44	0.111	0.41

Table 3-5. Summary of the globally averaged effective emission indices for 2015 scheduled air traffic by airplane size category. (Units = grams of emission/kilogram of fuel burned).

Airplane Size	EI(NOx)	EI(HC)	EI(CO)
Turboprop	11.4	0.5	5.0
50-90 passengers	8.5	1.6	16.1
91-120 passengers	10.8	1.3	10.4
121-170 passengers	12.4	0.7	5.7
171-240 passengers	13.4	0.5	5.1
241-400 passengers	15.7	0.6	3.5
> 400 passengers	15.0	0.3	1.7
Freighter	15.2	1.2	4.3

3.3 Seasonal Variation in Air Traffic

Scheduled air traffic varies over the year with more travel during some seasons than others. This seasonal variation in emissions is most marked in the North Atlantic flight corridor as was noted earlier (Baughcum, *et al.*, 1996a). Since global atmospheric models must account for seasonal variations in winds and temperatures, it is important to try to provide emission scenarios which reflect as much realism in their seasonal response as possible.

No explicit calculation of seasonal variation was done in this analysis. A first-order approach was taken in which it was assumed that the seasonal variation in 2015 would match that calculated previously for 1992. To implement this, a scaling factor representing the seasonal variation for each grid cell in the 3-dimensional array (1 degree latitude x 1 degree longitude x 1 km pressure altitude) was calculated using our earlier analysis for each month of 1992. This scaling factor was then applied to each grid cell of the 2015 scenario to produce monthly 2015 scenarios. If emissions were projected in 2015 in a grid cell for which no emissions occurred during 1992, no seasonal variation was imposed. Thus, twelve 3-dimensional data files corresponding to each month for 2015 were calculated and supplied to NASA for use in the assessment calculations. The global totals for each month are summarized in Table 3-6.

When the values in each column of Table 3-6 are weighted for the number of days in each month and totaled, the totals differ slightly from the yearly totals given in Table 3-1 instead of matching exactly as would be expected. These minor differences are due to subtleties of the algorithm employed to estimate 2015 seasonal variation based on the 1992 results.

Table 3-6. Projected fuel use and emissions for 2015 based on the seasonality calculated for 1992 (Baughcum, *et al.*, 1996a). (units = million kg/day)

Month	Fuel	NOx	HC	CO
January	640	9.04	0.43	2.87
February	663	9.38	0.46	2.99
March	665	9.41	0.46	2.99
April	673	9.52	0.46	3.00
May	683	9.66	0.47	3.06
June	704	9.97	0.48	3.13
July	721	10.20	0.49	3.18
august	723	10.23	0.49	3.18
September	709	10.03	0.49	3.14
October	697	9.87	0.48	3.12
November	715	10.11	0.49	3.15
December	713	10.06	0.49	3.15

3.4 Comparison with Previous 2015 Projections

Subsonic emission scenarios for the year 2015 have been developed as part of past studies done to assess the possible effect of a fleet of High Speed Civil Transports (HSCT) on the global atmosphere (Baughcum *et al.*, 1994; Baughcum and Henderson, 1995). The subsonic emissions scenarios in these studies were not intended to provide a rigorous estimate of global emissions and fuel burn totals for the subsonic fleet as was the case in the current study. Instead, they were intended to provide a baseline from which to assess the relative effect on global aircraft emissions and fuel burn that the introduction of HSCTs to the world aircraft fleet would have.

There are significant differences between the subsonic scenarios developed in the past and that which was developed in the current study in both the way aircraft performance and emissions technology were forecast and in the methodology used to calculate global emissions. These differences manifest themselves most clearly in the global NOx totals given in Table 3-1 which differ from one another by approximately 46%. Table 3-7 summarizes the differences in assumptions and methodology between the current study and those of Baughcum and Henderson (1995).

As shown in Table 3-7, the most significant differences between the current and previous studies are associated with technology assumptions. In the current study it was assumed that in the year 2015, aircraft engine cycles based

Table 3-7. Comparison of assumptions made and methodology used to create the current and previous (Baughcum and Henderson, 1995) scheduled aircraft fleet global emissions projections for the year 2015.

	Previous 2015 estimate (Baughcum and Henderson, 1995)	Current 2015 estimate (This Work)	Estimated effect on the difference in global NOx (relative to Baughcum and Henderson, 1995)
Emissions Technology Assumptions	*Dramatic Reductions in Emissions*: Based on the assumption that *all* of the engines in the 2015 fleet will be at an assumed state of the art 2005 technology level	*Aggressive Reductions in emissions*: Partial penetration of dual annular combustor (DAC) and other low NOx emissions technologies; assumptions based on detailed analysis of how phasing in of low emissions technology into the fleet is likely to occur	+25% to +30%
Aircraft Fleet Representation	10 Unique aircraft/engine combinations having the lowest emitting engines available in 1990 as baselines, with new technology assumptions applied to these	110 unique aircraft/engine combinations having a distribution of aircraft/engine types based on detailed Boeing technology and fleet mix projections	+5% to +10%
Emissions Calculation Method	Boeing Method 1	Boeing Method 2	+10%

on technology that is twenty years old or older (i.e. technology being implemented at the present time) will still be present in the scheduled aircraft fleet. The technology improvement estimates for the year 2015 made in the current study and discussed in section 2.3 of this report are aggressive but based upon a detailed evaluation of how the phasing of low emissions technology into the commercial aircraft fleet is likely to occur in the near future.

In the previous studies, projections of aircraft fleet emissions and performance characteristics were based on the assumption that all of the engines in the 2015 fleet would be at an assumed state of the art 2005 technology level. The emissions characteristics of eight advanced engines in production at the time of the previous studies (i.e. engines having relatively low LTO NOx) were ratioed down by 30 to 40 percent. The emission characteristics of these particular engines were used to represent similar engine types on every aircraft in the 2015 scheduled aircraft fleet.

A second difference between the current and previous 2015 studies shown in Table 3-7 is the level of detail used when modeling the aircraft fleet make-up. Differences in this level of detail can have a significant effect on emissions and fuel burn projections.

In the current study, the scheduled aircraft fleet was represented by 110 aircraft/engine combinations. In the study of Baughcum and Henderson (1995), the scheduled fleet was divided into 10 passenger classes based on aircraft seat count and 6 cargo classes based on aircraft cargo capacity. For each cargo or passenger class, one of ten specific aircraft/engine combinations was used to represent the performance and emissions for every aircraft in that class.

Figures 3-6 and 3-7 show the effect that the representation of the entire scheduled aircraft fleet by only ten aircraft/engine combinations has on the distribution of fleet fuel burn and NOx emissions over cruise altitudes. Instead of being distributed more evenly over the full range of cruise altitudes, as it is for the current study, the fleet fuel burn and NOx emissions projected by Baughcum and Henderson (1995) are biased toward the 11 to 12 km altitude range. This bias is directly related to the small number of aircraft/engine combinations that were used to represent the 2015 fleet.

Figure 3-8 gives a comparison of the fleet NOx technology levels for 1992 (Baughcum *et al.*, 1996) and those projected by the current study and by Baughcum and Henderson (1995). For each study, the fraction of total global fleet fuel burned by aircraft having landing take-off (LTO) cycle NOx emissions that are a given percentage above or below the ICAO CAEP/2 NOx limit is shown. Although relative LTO cycle NOx levels do not directly correspond with relative NOx emission levels over an entire flight, they are useful as a general indicator of the NOx emissions technology level of an engine.

Figure 3-8 clearly shows the effects of the marked differences in the NOx technology assumptions between the current study and that of Baughcum and Henderson (1995). The distribution associated with the current study shows a reasonable evolutionary shift in the LTO NOx distribution to lower levels between 1992 and 2015. In contrast, the distribution associated with the previous study of Baughcum and Henderson (1995) implies that by 2015 all engines in the scheduled aircraft fleet will have LTO NOx emissions that are 50% below the CAEP/2 limit or more. For comparison, engines having today's very best low emissions technology have LTO NOx emissions that range from 40% to 60% below the CAEP/2 limit.

In addition to the differences discussed above, different calculation methods were used to project global fuel burn for the previous and current studies. In the previous studies, Boeing Method #1 was utilized to calculate global fuel burn and emissions while in the current study Boeing Method #2 was used. Boeing Method #2 is a refined version of Boeing Method #1. Differences between these methods are discussed by Baughcum *et al.*, 1996. Comparisons between inventory calculations done using each of the two Boeing methods show that NOx values calculated using Boeing Method #2 are roughly 10% higher than those calculated using Boeing Method #1. Therefore, roughly 10% of the increase in globally average effective EI(NOx) over the previous study results can be attributed to the use of different emissions calculation methodologies.

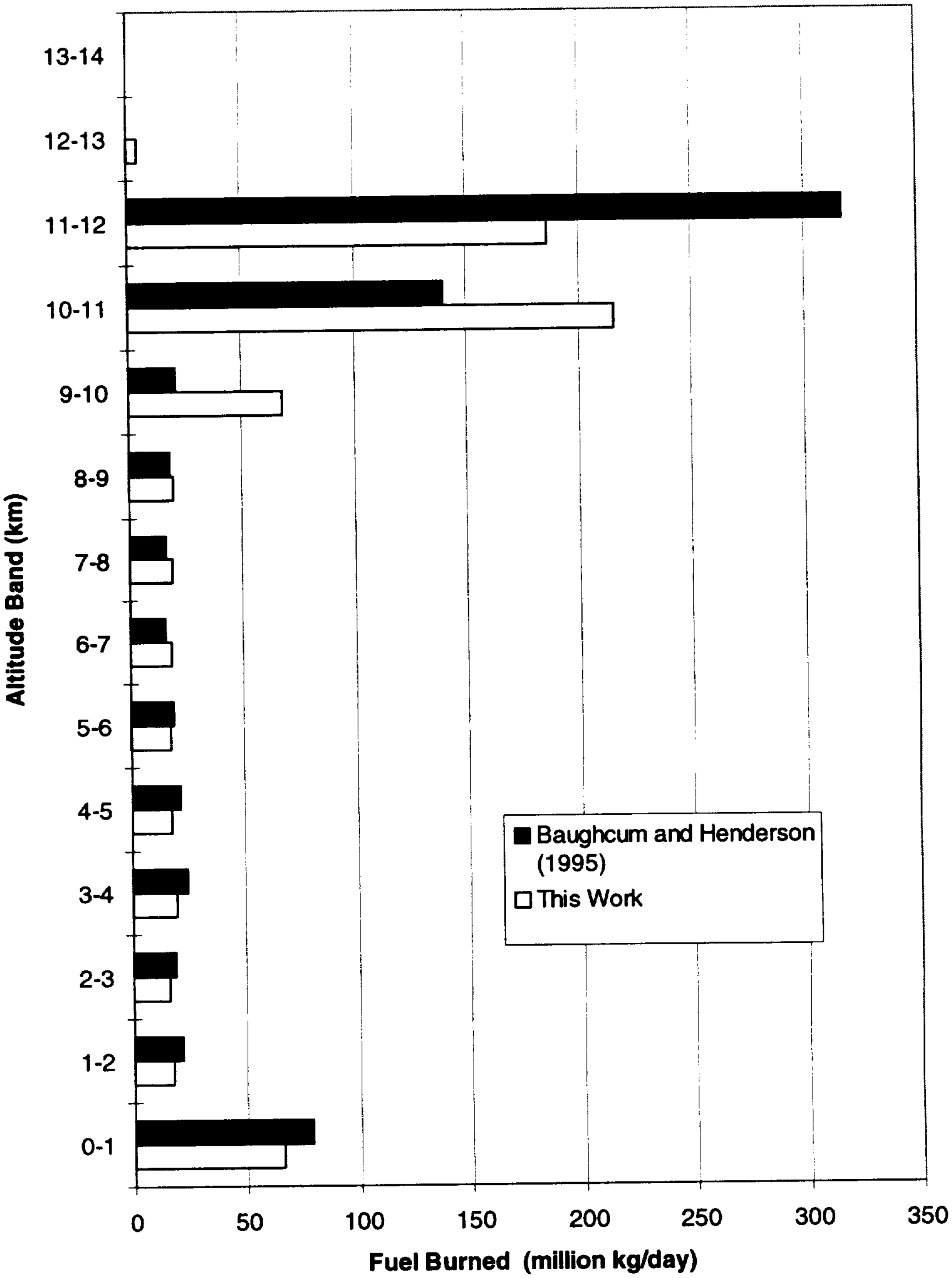

Figure 3-6. Comparison of the altitude distribution for fuel use for 2015 between this work and the earlier 2015 projection (Baughcum and Henderson, 1995).

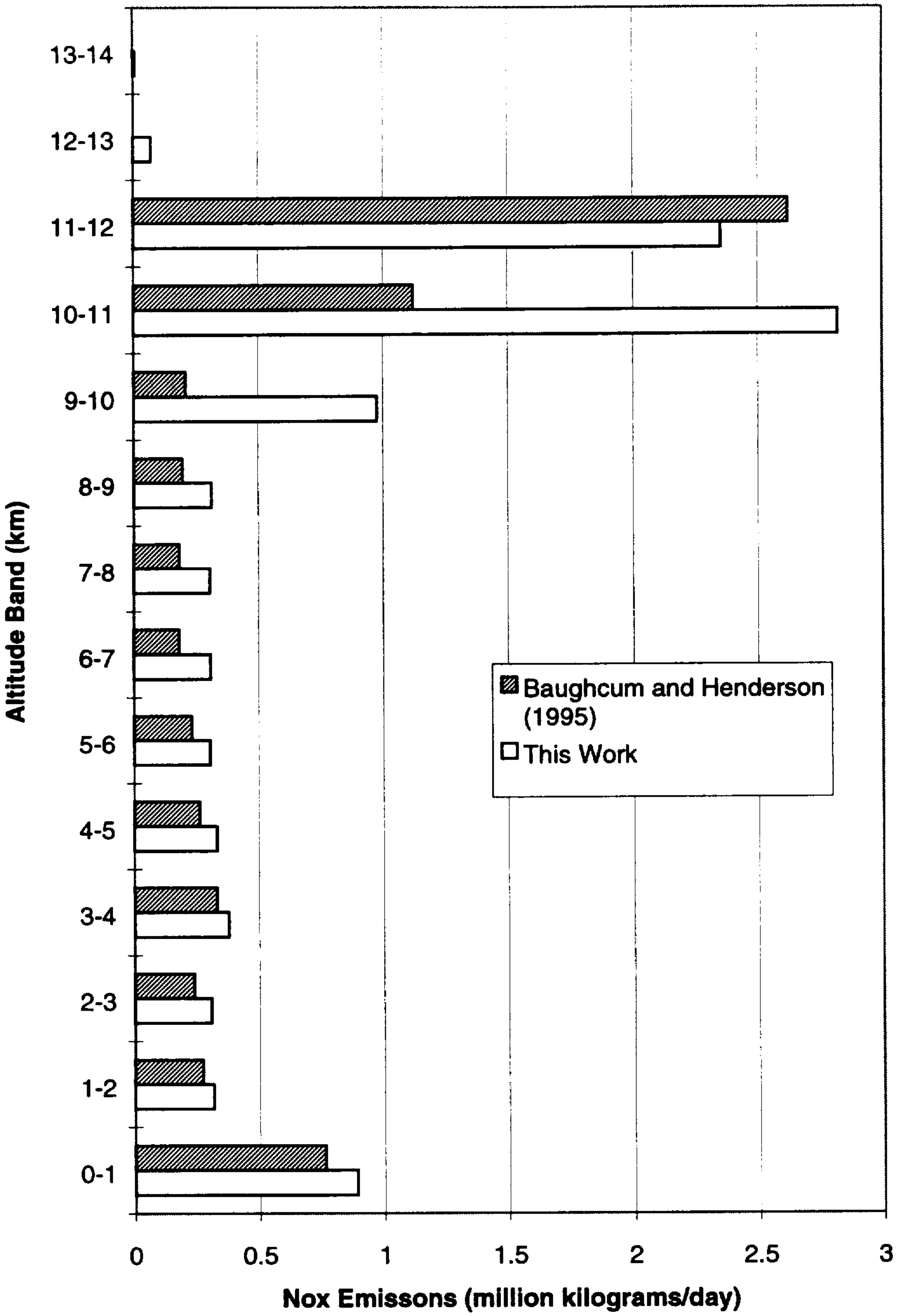

Figure 3-7. Comparison of the altitude distribution for NOx of the current forecast for 2015 and the earlier 2015 projection (Baughcum and Henderson, 1995).

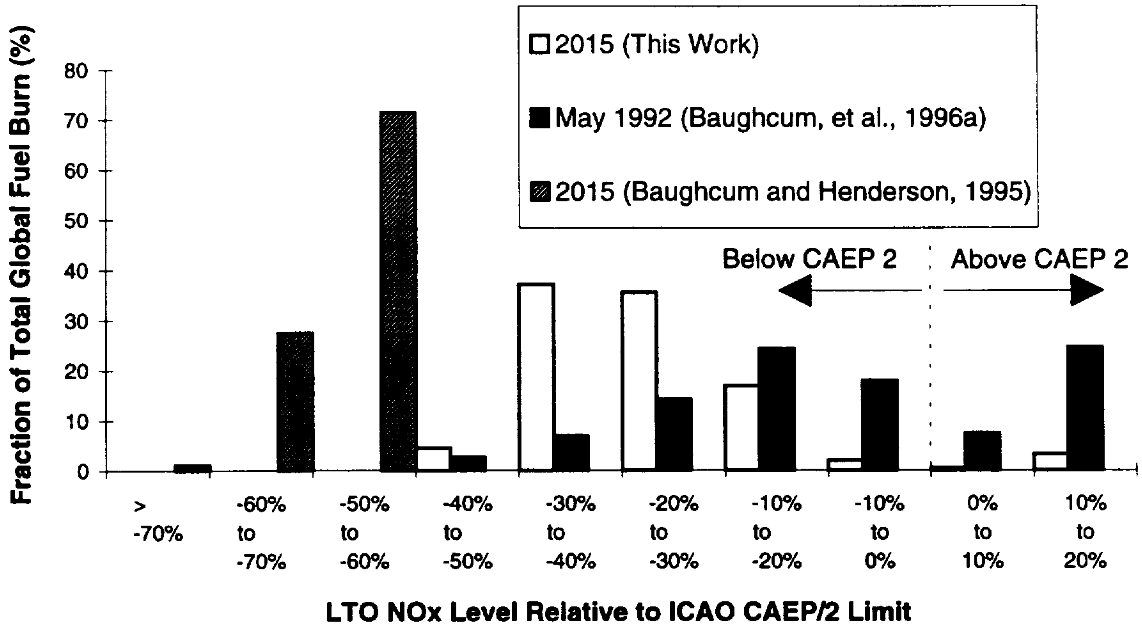

Figure 3-8. Fraction of total global fuel burned by aircraft having LTO NOx emissions at a given level relative to the CAEP/2 NOx limit for 1992 (Baughcum *et al.*,1996a), 2015 (current study) and 2015 (Baughcum and Henderson, 1995).

4. Summary and Conclusions

A new emission scenario for scheduled air traffic in 2015 has been developed. Passenger demand, aircraft performance, and aircraft engine emission characteristics were forecast to 2015. Fuel burned and emissions (NOx, hydrocarbons, carbon monoxide) were then calculated onto a 1 degree latitude x 1 degree longitude x 1 kilometer pressure altitude grid and delivered electronically to NASA Langley Research Center.

Global jet fuel use by scheduled air traffic was projected to be 684 million kg/day, which is an increase of 164 % of that calculated previously for 1992 (Baughcum, *et al.,* 1996). Global NOx emissions were calculated to be 9.7 million kg/day, which is an increase of 187% compared to 1992. Total hydrocarbon emissions were calculated to be slightly lower (by 11%) than 1992, while total carbon monoxide emissions were calculated to increase by 125%.

The global fuel consumption in this forecast of 2015 is approximately 3.9% lower than that projected previously for 2015 (Baughcum and Henderson, 1995). Global NOx emissions are calculated to be 46% higher in this forecast compared to the earlier 2015 scenario due to changes in assumptions regarding the level of future NOx reduction technology and differences in calculation methodology.

In this work, the 2015 scheduled fleet was represented by a large number of current and projected aircraft (110 compared to 10 generic types in the earlier study) and a much wider range of engine characteristics. Unlike the earlier work, retirement and replacement of existing aircraft was treated explicitly (the earlier study assumed that the average technology in 2015 corresponded to new 2005 aircraft). The current study also considered in more depth how new emissions technology would be introduced into the fleet, rather than assuming a dramatic improvement across all engine types.

The emission scenario is available from NASA by contacting Karen Sage (sage@uadp2.larc.nasa.gov).

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Appendix A - World Traffic by Market

Appendix A
World Traffic by Market
RPMs in Billions

Traffic Flow	**1970**	**1975**	**1980**	**1985**	**1990**	**1991**
CIS	46.912	71.907	94.015	109.269	139.366	129.903
CANADA	5.014	8.747	12.391	11.567	15.363	13.520
USA	109.491	135.999	203.658	277.902	345.819	338.039
LATIN AMERICA	4.534	9.795	16.837	22.312	22.102	21.971
EUROPE	8.456	13.743	18.557	24.036	33.763	32.354
AFRICA	1.261	2.353	3.038	4.998	5.468	4.945
INDIAN SUB.	1.694	2.042	3.450	5.703	6.273	6.314
M.E.	0.428	1.229	3.919	4.683	5.584	5.347
ASIA	1.286	2.762	4.570	6.398	11.335	11.989
CHINA	0.326	0.685	1.738	5.449	11.661	15.449
JAPAN	5.083	11.166	18.650	20.831	31.632	33.773
OCEANIA	3.739	5.007	6.199	8.118	9.871	12.767
DOMESTIC TOTAL	**188.226**	**265.435**	**387.023**	**501.265**	**638.238**	**626.370**
INTRA AFRICA	1.943	3.124	3.894	4.105	5.166	4.622
AFR- INDIAN SUB.	0.272	0.432	0.460	0.624	0.537	0.530
AFR- M.E.	1.080	1.566	3.488	3.838	5.401	3.949
AFR-OCEANIA	0.180	0.261	0.245	0.378	0.429	0.549
INTRA ASIA	3.834	7.810	14.787	21.743	44.932	51.115
ASIA-AFRICA	0.009	0.047	0.084	0.407	0.547	0.808
ASIA-EUROPE	4.183	11.759	23.145	33.065	57.475	52.692
CIS INT'L	2.285	5.598	7.541	9.859	14.977	13.072
INTRA EUROPE	29.619	52.316	65.248	81.367	126.494	112.580
EUROPE-AFRICA	11.482	16.910	26.655	32.079	33.439	30.095
EUROPE-INDIAN SUB.	1.450	4.153	6.330	7.355	10.679	9.291
EUROPE-L.AMER	4.427	10.706	15.301	18.825	29.788	30.782
EUROPE-M.E.	6.113	12.176	23.628	28.695	23.712	20.136
INTRA INDIA SUB.	0.303	0.351	0.615	0.805	0.938	0.947
INDIAN SUB.-ASIA	0.949	1.369	2.449	3.135	4.969	4.345
INDIAN SUB.-M.E.	1.070	2.186	5.002	7.755	8.900	8.007
INDIAN SUB.-OCE.	0.000	0.457	0.960	0.266	0.273	0.142
INTRA L.AMER	3.813	6.247	8.582	6.991	8.779	8.412
LATIN AMER - AFRICA	0.415	1.034	0.973	0.390	0.643	0.427
LATIN AMER- OCEANIA	0.007	0.022	0.086	0.059	0.253	0.221
INTRA M.E.	1.639	5.442	6.874	8.008	10.125	8.773
M.E.-ASIA	2.288	3.896	7.073	12.355	4.065	5.901
M.E.-OCEANIA	0.000	0.000	0.094	0.158	0.780	0.398
INTRA N. AMER	4.116	6.270	9.128	10.672	13.248	13.619
N.AMER-AFRICA	0.101	0.289	0.668	1.172	1.015	0.868
N.AMER-ASIA	7.508	13.879	25.934	40.968	77.956	80.610
N.AMER-EUROPE	44.829	58.200	85.132	97.834	141.509	129.336
N.AMER-L.AMER	9.996	14.434	24.933	23.875	34.615	34.672
N.AMER-M.E.	0.613	0.679	2.747	2.480	3.133	2.697
INTRA OCEANIA	0.914	1.966	2.684	3.028	5.238	6.167
OCEANIA-ASIA	2.179	5.611	8.212	11.045	27.560	28.756
OCEANIA-N.AMER	1.664	2.744	5.359	8.015	12.518	12.468
US MAC(INT'L)	5.041	2.395	1.224	2.610	3.745	5.657
INT'L TOTAL	**154.322**	**254.330**	**389.538**	**483.960**	**713.840**	**682.643**
WORLD TOTAL	**342.548**	**519.765**	**776.561**	**985.225**	**1352.078**	**1309.013**

Appendix A (cont.)
World Traffic by Market
RPMs in Billions

Traffic Flow	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**
CIS	85.227	55.764	45.169	42.007	44.192	47.462
CANADA	10.780	10.568	10.986	11.513	11.859	12.191
USA	354.716	361.860	388.029	404.714	420.093	438.157
LATIN AMERICA	22.502	22.473	23.820	24.535	25.737	27.153
EUROPE	36.306	37.312	39.012	40.846	42.602	44.306
AFRICA	4.497	4.005	4.205	4.390	4.587	4.780
INDIAN SUB.	6.524	5.663	6.343	6.958	7.584	8.237
M.E.	5.598	5.906	6.369	6.860	7.196	7.627
ASIA	12.457	13.116	15.017	16.053	17.096	18.173
CHINA	19.203	22.958	27.351	32.821	38.020	45.149
JAPAN	35.176	35.177	36.810	38.282	39.890	41.366
OCEANIA	12.984	15.326	16.860	17.804	18.677	19.554
DOMESTIC TOTAL	**605.972**	**590.129**	**619.970**	**646.783**	**677.533**	**714.155**
INTRA AFRICA	5.098	5.382	5.489	5.769	6.098	6.464
AFR- INDIAN SUB.	0.606	0.733	0.845	0.877	0.912	0.949
AFR- M.E.	4.754	5.163	5.406	5.649	5.965	6.341
AFR-OCEANIA	0.727	0.701	0.759	0.797	0.834	0.872
INTRA ASIA	55.941	60.056	67.140	72.108	77.733	83.485
ASIA-AFRICA	0.863	1.129	1.277	1.352	1.433	1.520
ASIA-EUROPE	64.653	69.954	78.237	83.479	89.907	96.650
CIS INT'L	11.820	14.874	17.105	18.336	19.711	21.210
INTRA EUROPE	125.490	135.696	147.773	156.196	163.693	171.223
EUROPE-AFRICA	33.209	34.375	36.369	37.933	39.678	41.542
EUROPE-INDIAN SUB.	9.496	10.788	11.521	12.339	13.117	13.891
EUROPE-L.AMER	35.765	38.554	43.131	45.417	47.643	50.072
EUROPE-M.E.	20.012	22.100	24.120	25.616	27.076	28.565
INTRA INDIA SUB.	1.045	1.082	1.160	1.255	1.348	1.445
INDIAN SUB.-ASIA	4.588	4.982	5.258	5.536	5.869	6.197
INDIAN SUB.-M.E.	9.798	10.679	11.908	12.670	13.544	14.479
INDIAN SUB.-OCE.	0.221	0.031	0.000	0.124	0.266	0.280
INTRA L.AMER	8.712	8.886	9.579	9.847	10.201	10.650
LATIN AMER - AFRICA	0.431	0.263	0.270	0.285	0.309	0.336
LATIN AMER- OCEANIA	0.282	0.298	0.447	0.501	0.533	0.570
INTRA M.E.	10.146	10.564	11.240	11.858	12.487	13.198
M.E.-ASIA	8.054	8.649	9.748	10.186	10.696	11.220
M.E.-OCEANIA	0.352	0.387	0.424	0.446	0.471	0.498
INTRA N. AMER	14.408	15.898	16.645	17.427	18.055	18.632
N.AMER-AFRICA	1.057	1.479	1.558	1.638	1.703	1.780
N.AMER-ASIA	87.100	91.803	97.036	104.022	112.032	120.658
N.AMER-EUROPE	151.353	159.525	166.689	172.689	181.151	189.303
N.AMER-L.AMER	38.670	41.899	44.874	46.938	49.144	51.798
N.AMER-M.E.	3.502	3.988	4.786	5.059	5.302	5.583
INTRA OCEANIA	6.633	6.835	7.298	7.896	8.504	9.125
OCEANIA-ASIA	30.350	33.597	36.587	39.623	42.753	45.874
OCEANIA-N.AMER	12.867	13.111	12.698	13.295	13.960	14.742
US MAC(INT'L)	2.312	2.339	2.111	2.240	2.303	2.301
INT'L TOTAL	**760.314**	**815.802**	**879.487**	**929.406**	**984.431**	**1041.455**
WORLD TOTAL	**1366.286**	**1405.931**	**1499.458**	**1576.189**	**1661.964**	**1755.610**