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# Aircraft Emission Scenarios Projected in Year 2015 for the NASA Technology Concept Aircraft (TCA) High Speed Civil Transport

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## Executive Summary


This report describes the development of new emission scenarios for high speed civil transports using the NASA Technology Concept Airplane (TCA). This emission scenario was developed under the NASA High Speed Research Phase II contract NAS1-20220, Task Assignment 19.

Emission scenarios for fleets of approximately 500 and 1000 high speed civil transports have been calculated on a universal airline network using the NASA TCA performance and emissions characteristics (EI(NOx)=5 at supersonic cruise). In addition, the displacement in emissions from subsonic aircraft by the utilization of the HSCTs was calculated based on the year 2015 subsonic emission scenario calculated in a parallel activity and reported elsewhere. Fuel burned and emissions (NOx, hydrocarbons, and carbon monoxide) were 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 fleets of 500 and 1000 active TCA HSCTs was calculated to be 198 and 375 million kilograms/day, respectively. This is approximately 12% less global fuel use for the TCA, compared to the Reference H HSCT model used in earlier HSCT scenario calculations that were the basis for the 1995 AESA assessment. The TCA is calculated to burn approximately 13 % less fuel above 17 kilometers altitude than did the Reference H aircraft. Assuming the same combustor technology in both, this is about 13% less NOx injected at altitudes above 17 kilometers. Supersonic cruising climb for the TCA occurs approximately 1 kilometer lower than for the Reference H HSCT used in previous HSCT scenario calculations.

The net effect on global fuel use by scheduled air traffic by the introduction of fleets of 500 and 1000 HSCTs, was an increase of 90 and 198 million kilograms/day, respectively, assuming year 2015 technology and accounting for the displacement of subsonic aircraft by HSCTs. Assuming EI(NOx)=5 combustor technology for the TCA, global NOx emissions from aircraft were calculated to decrease by 0.6 and 0.7 million kilograms/day for fleets of 500 and 1000 HSCTs, respectively. The displacement of emissions from the subsonic fleet by a supersonic fleet resulted in lower tropospheric NOx emissions relative to the all subsonic case.

These emission scenarios are available for use by atmospheric scientists conducting the Atmospheric Effects of Aviation Project (AEAP) modeling studies.

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## GLOSSARY

| | |
|---|---|
| AEAP | Atmospheric Effects of Aviation Project |
| 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 |
| GCD | Great circle distance |
| GE | General Electric |
| gm | gram |
| HC | Unburned hydrocarbon |
| $H_2O$ | Water |
| 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 on a given flight |
| 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 |
| RAM | Revenue air mile |

| | |
|---|---|
| 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) |
| $SO_2$ | Sulfur dioxide |
| TBE | Turbine bypass engine |
| TCA | Technology Concept Airplane (HSCT) |
| TOGW | Takeoff gross weight |
| ton | 2000 pounds |
| 3D | Three dimensional |

# 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 develop the technology for a supersonic commercial transport (HSCT) which will cause no significant impact to the stratospheric ozone layer. Within NASA, the Atmospheric Effects of Stratospheric Aircraft (AESA) project is responsible for assessing the effect of HSCT emissions. To support that assessment effort, Boeing was contracted to calculate three-dimensional scenarios of emissions from projected fleets of future subsonic and supersonic aircraft.

Three-dimensional scenarios of HSCT emissions have been reported earlier by both Boeing (Baughcum, *et al.*, 1994; Baughcum and Henderson, 1995) and by McDonnell Douglas (Landau, *et al.*, 1994; Metwally, 1996). The scenarios have been developed from projections of passenger demand for the year 2015 coupled with assumptions about the accessible HSCT market. These are then combined with projected HSCT performance and emissions engineering data to calculate the fuel use and emissions along the flight track for each projected flight. The results for fuel burned and emissions (NOx, hydrocarbons, and carbon monoxide) are then gridded onto a 1 degree latitude x 1 degree longitude x 1 km pressure altitude grid. These datafiles can then be used as input to two and three-dimensional chemical transport models to evaluate the effect of HSCT emissions. Earlier assessment results are tabulated in the reports of Stolarski and Wesoky (1993) and Stolarski, *et al.* (1995), as well as the published scientific literature.

The work described in this report is an update of the HSCT emission scenario reported earlier for the universal airline network (Baughcum and Henderson, 1995). The same passenger demand network and airplane schedules are used, but the aircraft technology and emission characteristics have been updated to those of the NASA Technology Concept Airplane (TCA) HSCT. This report briefly describes the results of that update.

The work described in this study was conducted under NASA Langley Contract NAS1-20220, Task 19. The NASA Langley Task Manager was Donald L. Maiden.

Within the Boeing HSCT engineering group, the principal investigator for the task was Steven L. Baughcum. Chief contributors from the market analysis group were Stephen Henderson, Richard Bateman, and Terry Higman.

## 2. Methodology

### 2.1 HSCT Network

The universal airline network used in this study was described in detail in an earlier report (Baughcum and Henderson, 1995). The network and departure schedules used in this study are identical to that earlier report. A brief summary of the approach, assumptions, and ground rules is described here.

The total passenger demand forecast for the year 2015 was created based on the Boeing Current Market Outlook, which projects demand by geographical regions. HSCT passenger demand and market penetration were then calculated from that projection. Due to the operating characteristics of the HSCT (sonic boom restrictions and high operating costs, particularly on short routes), only a certain subset of the total regional passenger demands are candidates for HSCT service. The suitability of the HSCT for the remaining passenger demand must be determined according to some logical assessment criteria.

One of the goals of the current fleet growth study is to determine how an increasing fleet of HSCTs would change the global distribution of emissions. Therefore, this study does not use a "static" set of criteria for determining the proportion of city-pair demand likely to be captured by the HSCT. Instead, demand captured by the HSCT was determined by a proprietary market penetration model developed within Boeing. The proportion of each city-pair market captured by the HSCT was found by:

$$P = f(R, T, F, Z, L_{min})$$

where

$P$ = percent of total passenger demand carried by the HSCT,
$R$ = range of the HSCT,
$T$ = Trip time saved versus a subsonic airplane,
$F$ = Fare premium over the subsonic airplane,
$Z$ = stop factor (whether the HSCT flight is non-stop or not), and
$L_{min}$ = the minimum load factor allowed on a flight.

The only explicit constraint operating in the penetration model is the prohibition of supersonic flight over land.

As the amount of time saved increased or the fare premium decreased or the number of stops decreased, the proportion of the passenger demand carried by the HSCT increased. If the application of the penetration model lowered the HSCT passenger demand on a city-pair to less than 180 passengers per day, that city-pair was dropped from the HSCT system. The penetration model was used to generate the two fleet sizes used in this study. The fare premium parameter (*F*) of the model was first adjusted so that the passenger demand carried by the HSCT in 2015 required approximately 500 Mach 2.4 airplanes, forming the baseline case for the calculation of HSCT emissions distribution. The fare premium parameter was then reduced so that the increased passenger demand required approximately 1000 Mach 2.4 airplanes, creating the alternate case. The average load factor was 65%.

The higher demand carried by the 1000 airplane fleet came from both an increased penetration on the same markets served by the 500 airplane fleet and an increase in the number of city-pairs served. The details of the network are described in Baughcum and Henderson (1995).

As was noted previously, the amount of trip time saved by the HSCT versus a subsonic airplane serving the same city-pair is one of the determinants of HSCT market penetration. Since it is assumed that the HSCT must fly at subsonic speeds over land masses, each potential HSCT city-pair route was examined to find the reasonable routing which minimized (or at least reduced) the percentage of the flight spent over land. The flight routing was accomplished by establishing "waypoints", a set of specific latitude-longitude positions which defined the HSCT flight path. (The HSCT flight path between waypoints was flown as a great circle.)

The utilization statistics are summarized in Table 2-1 below. Slight differences in departure statistics arise because the TCA design is a 300 passenger aircraft while the Reference H design was for 309 passengers. The nonlinear nature of both the penetration model and the scheduling model made it difficult to exactly achieve the goal of 500 and 1000 airplane HSCT fleets. The fleet size was adjusted by varying the fare premium in the penetration model so that the nominal "500" unit Mach 2.4 fleet was actually 499 units and the nominal "1000" unit fleet was actually 991 units. These were felt to be close enough to the target fleet sizes for these parametric studies and additional iterations were not performed. In both cases, the fleet size refers to the active number of aircraft flying to meet that passenger demand, not the number of aircraft manufactured. The manufactured fleet would be larger to account for spares, training, and non-optimum utilization of the network.

Because of its speed, the HSCT has the ability to serve a large set of cities and still remain within the preference/curfew time "windows", which are always defined in local time. It is also worth noting that the calculated block hours are high (16 hours/day) since the assumption has been made that the HSCT would be utilized as effectively as possible.

**Table 2-1.** Utilization statistics for the universal airline HSCT network.

| | Mach 2.4 | Mach 2.4 |
|---|---|---|
| Units | 499 | 991 |
| Average Stage Length (nautical miles) | 3555 | 3026 |
| Average Daily Use (hours) | 21.95 | 22.24 |
| Average Hours/Segment | 3.67 | 3.30 |
| Average Hours/Trip | 4.26 | 3.78 |
| Average Block Hours/Day | 16.00 | 16.10 |
| Percent of Subsonic Trip Time | 49.97 | 53.25 |
| Network Flight Path % of GCD | 103.98 | 106.16 |
| % of Trip in Supersonic Cruise | 75.16 | 71.18 |
| % of Trip in Subsonic Cruise | 12.52 | 15.46 |
| Percent Nonstop Trips | 87.88 | 89.39 |
| Average Trip Load Factor | 65.16 | 65.09 |
| Annual RPMs (Billion) | 551 | 1,043 |
| Annual ASMs (Billion) | 846 | 1,602 |
| Annual Departures | 793,510 | 1,765,140 |
| Annual RAMs (GCD - Million) | 2,713 | 5,031 |
| Annual RAMs (Path - Million) | 2,821 | 5,341 |

## 2.2 HSCT (TCA) Performance and Emissions Calculations

The new HSCT emission scenarios reported here were calculated for the NASA Technology Concept Airplane (TCA). This design is for a Mach 2.4, 5000 nautical mile range airplane carrying approximately 300 passengers. The design engines are mixed flow turbofans with very low NOx emission combustors. The design goal for the combustor program is a NOx emission index of 5 grams of NOx (as $NO_2$) per kilogram fuel burned at supersonic cruise conditions. By comparison, the Reference H HSCT was a 309 passenger, Mach 2.4, 5000 nautical mile range airplane with turbine bypass engines.

As will be discussed in the results section, the TCA differs from the HSCT model (Reference H) used in the development of the earlier HSCT scenarios in two key ways - it flies somewhat lower and it is more fuel efficient. This will be illustrated more clearly in Section 3.

Emissions data for NOx, CO, and hydrocarbons were provided by GE/P&W for a generic HSCT combustor with a nominal NOx emission index at supersonic cruise of approximately 5 grams NOx (as $NO_2$) per kilogram of fuel. Since the technology for these combustors and engines is still very early in the development stage, the EI(NOx) above 13 kilometers flight altitude were normalized to a value of 5.0 for use in the parametric studies conducted by the NASA AESA project. It is expected that the HSCT must have very efficient (greater than 99.9%) combustors, and thus the EI(hydrocarbons) and EI(CO) were fixed at 0.3 and 2.9, respectively, at all flight conditions.

The mission profile procedures were described in detail in our previous NASA contractor report (Baughcum, *et al.*, 1994). 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
- 5 minute taxi-in

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 were described in our previous NASA contractor report. (Baughcum, *et al.*, 1994)

HSCT flight profiles of fuel burn and emissions were calculated from these performance and emissions data for each HSCT mission. These profiles combined with projected HSCT flight frequencies were then used to calculate the three-dimensional database, as described in our previous contractor report. (Baughcum, *et al.*, 1994)

When calculating the flight profiles, all aircraft were assumed to fly according to design performance. For subsonic aircraft, cruise altitudes were calculated as a climbing cruise with the optimum 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.

## 2.3 Year 2015 Subsonic Fleet Displacement

The introduction of a fleet of high speed civil transports will displace some subsonic aircraft. Recently, a new 3-dimensional scenario for scheduled air traffic in 2015 was completed (Baughcum, *et al.*, 1998). The same passenger demand forecast and technology forecast was then used to calculate the displacement of subsonic aircraft and their emissions by the introduction of the supersonic aircraft. To do this, it was assumed that the total passenger demand would remain unchanged. Thus, the demand forecast for a given city-pair for the HSCT was subtracted from the total passenger flow for that city-pair and then the subsonic traffic schedule was recalculated. The results are described in Section 3.

## 2.4 Emission Calculation Procedures

All aircraft were assumed to fly according to design optimum performance. Altitudes and mission profiles were calculated based on the performance of the aircraft for its mission weight. Air traffic control constraints on routings were not considered. 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 of the city-pairs. The HSCT was flown along great circle routes between these waypoints. For all flights, prevailing winds were not considered, based on the assumption that wind effects would largely be canceled out for round trips.

To calculate the global inventory of aircraft emissions, a computer model was developed which basically combines scheduling data (city pairs, 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 the fuel flow rate. The GAEC model was described in more detail in the earlier report (Baughcum, *et al.*, 1994).

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 year 2015 subsonic aircraft, emissions of nitrogen oxides (NOx), hydrocarbons (HC) and carbon monoxide (CO) were projected from the ground level emission indices reported to the International Civil Aviation Organization (ICAO) for current aircraft (as described in Baughcum, *et al.,* 1998). These measurements are reported at four thrust settings. The Boeing fuel flow correlation methodology (Boeing Method #2) was used to calculate emission indices for different flight phases, corrected for ambient temperature, pressure, and humidity. (Baughcum, *et al.,* 1996)

Subsonic aircraft emission scenarios were calculated using the same technology improvements as reported in the latest 2015 scenarios. (Baughcum, *et al.*, 1998) Emission scenarios for scheduled subsonic air traffic were calculated for the cases of fleets of 0, approximately 500, and approximately 1000 HSCTs on the universal airline network. Displacement of subsonic air traffic by HSCTs on individual routes was explicitly taken into account. The results are described in Section 3 of this report.

Distributions of fuel usage and emissions were calculated for 1° latitude x 1° longitude x 1 km pressure altitude cells. The altitudes used are pressure altitudes, not geometrical altitudes. 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 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. Results

### 3.1 Global Totals

A summary of the network statistics is shown in Table 3-1, comparing the earlier results with the current work. The TCA cruises supersonically at a lower altitude and is more fuel efficient than the old Reference H airplane used in the earlier scenario development and in the earlier AESA assessments.

**Table 3-1.** Summary of departure statistics for HSCT networks.

| | Reference H HSCT (Baughcum and Henderson, 1995) | TCA HSCT (This Work) | TCA HSCT (This Work) |
|---|---|---|---|
| Number of Aircraft | 499 | 499 | 991 |
| Number of city pairs | 243 | 243 | 392 |
| Total daily departures | 2,174 | 2,172 | 4,820 |
| Total distance (miles/day) | 7,728,939 | 7,724,458 | 14,590,722 |
| Total Fuel (million lbs/day) | 509.46 | 435.7 | 827.3 |
| Maximum flight altitude (feet) | 67,854 | 64,411 | 64,423 |
| Minimum cruise altitude (feet) | 57,547 | 55,752 | 55,769 |

The fuel use and emissions for the different HSCT scenarios are summarized in Table 3-2 which shows the new TCA results and those calculated earlier for the Reference H model of the HSCT. The TCA uses approximately 12% less fuel globally than the Reference H HSCT when flown over the same network. The TCA burns approximately 13 % less fuel above 17 kilometers altitudes than did the Reference H aircraft. Assuming the same combustor technology in both, this is about 13% less NOx injected at altitudes above 17 kilometers. The assessment results (Stolarski, *et al.*, 1995) have shown that the calculated ozone depletion is sensitive to the flight altitudes and the amount of NOx emitted at higher altitudes.

**Table 3-2.** Summary of global fuel burned and emissions calculated for fleets of 500 and 1000 active HSCTs. (units = $10^6$ kilograms/day) (NOx is in units of $NO_2$ gram equivalent)

| Fleet | Reference | Fuel | NOx | HC | CO |
|---|---|---|---|---|---|
| 500 active HSCTs (TCA) | This work | 198 | 1.01 | 0.06 | 0.57 |
| 500 active HSCTs (Reference H) | Baughcum and Henderson, 1995 | 225 | 1.40 | 0.08 | 0.66 |
| 1000 active HSCTs (TCA) | This work | 375 | 1.93 | 0.11 | 1.08 |
| 1000 active HSCTs (Reference H) | Baughcum and Henderson, 1995 | 429 | 2.71 | 0.16 | 1.30 |

The global total fuel use and emissions calculated for the projected 2015 subsonic fleet are summarized in Table 3-3. These results show the amount of fuel burned and emissions calculated for the all subsonic fleet in 2015 and for the subsonic fleet in the presence of fleets of 500 and 1000 active HSCTs. It also tabulates the displacement of emissions by the subsonic fleet and the net change in total global emissions due to scheduled aircraft by the introduction of fleets of high speed civil transports, based on the NASA technology concept airplane (TCA). To put these results into perspective with total aviation sources, it would be necessary to combine the results for scheduled subsonic and HSCT aircraft (this work) with those projected for charter, military, general aviation, and domestic CIS/China (Landau, *et al.*, 1994; Mortlock and van Alstyne, 1998). That is beyond the scope of the current work.

It seems very unlikely that large fleets of supersonic transports would be in operation by 2015 and thus supersonic fleets of this size would arise in later years in which the overall subsonic fleet would be larger. The fraction of the total air traffic emissions due to supersonic aircraft will depend on both the size of the supersonic fleet and the existing subsonic fleet.

**Table 3-3.** Summary of global fuel use and emissions for projected 2015 fleets of subsonic aircraft. (units = $10^6$ kilograms/day) (NOx is in units of $NO_2$ gram equivalent)

| Scenario | Fuel | NOx | HC | CO |
|---|---|---|---|---|
| 2015 scheduled air traffic (no HSCT fleet) | 684 | 9.67 | 0.47 | 3.06 |
| 2015 subsonic fleet in the presence of 500 active HSCTs | 576 | 8.06 | 0.43 | 2.77 |
| 2015 subsonic fleet in the presence of 1000 active HSCTs | 506 | 7.03 | 0.41 | 2.61 |
| Change in subsonic emissions due to 500 active HSCTs | -108 | -1.62 | -0.04 | -0.29 |
| Change in subsonic emissions due to 1000 active HSCTs | -178 | -2.65 | -0.07 | -0.45 |
| Net change in emissions from scheduled air traffic with 500 active HSCTs | 90 | -0.61 | 0.02 | 0.27 |
| Net change in emissions from scheduled air traffic with 1000 active HSCTs | 198 | -0.72 | 0.04 | 0.63 |

### 3.2 Geographical distribution

The geographical distribution of the emission scenarios is illustrated in Figure 3-1, which shows the daily NOx emissions from a fleet of 500 Mach 2.4 (EI(NOx)=5) TCA's on the universal airline network. The top panel shows NOx emissions as a function of altitude and latitude (summed over longitude). This represents the input to a 2-dimensional (altitude and latitude) stratospheric chemistry models, such as those used in the AESA assessment. Peak emissions occur at supersonic cruise at northern mid-latitudes. The bottom panel illustrates the route segments occurring above 13 kilometers, which correspond to supersonic climb and supersonic climbing cruise.

The altitude distribution of the TCA is shown more clearly in Figure 3-2, which shows the fraction of the TCA fuel use as a function of altitude for fleets of both 500 and 1000 TCAs. As the market develops for larger aircraft, the average mission length changes and the fleet altitude distribution changes as well.

As noted earlier, the TCA flies lowers by approximately one kilometer than did the Reference H HSCT used in the earlier scenario calculations. Figure 3-3 compares the altitude distributions of the two HSCT models.

The displacement of subsonic flights by supersonic aircraft results in fewer aircraft and thus fewer emissions by subsonic aircraft. Figures 3-4 and 3-5 show the change in fuel use and NOx emissions, respectively, as a function of altitude to the subsonic fleet due to the presence of 500 and 1000 active TCA fleets. The largest changes are calculated at subsonic cruise altitudes as would be expected.

The net change in emissions due to the introduction of TCA fleets is shown in figures 3-6 and 3-7 for fuel use and NOx, respectively. Net fuel use at subsonic cruise altitudes (9-12 kilometers) was calculated to decrease while fuel use at higher altitudes (where no subsonic aircraft fly) increases. A net increase in fuel use in the 0-1 kilometer band was also calculated. For NOx, a net decrease in tropospheric emissions was calculated assuming the TCA combustor EI(NOx) was approximately 5. Since this EI(NOx) is lower than that projected for subsonic aircraft in 2015, a net decrease is calculated at altitudes below 12 kilometers. The introduction of the supersonic aircraft would cause an increase in NOx emissions at altitudes above 13 kilometers.

The calculated fuel burned and emissions as a function of altitude for the TCA scenarios are tabulated in Appendix A. The calculated subsonic emissions for 2015 as a function of altitude are also tabulated in Appendix A.

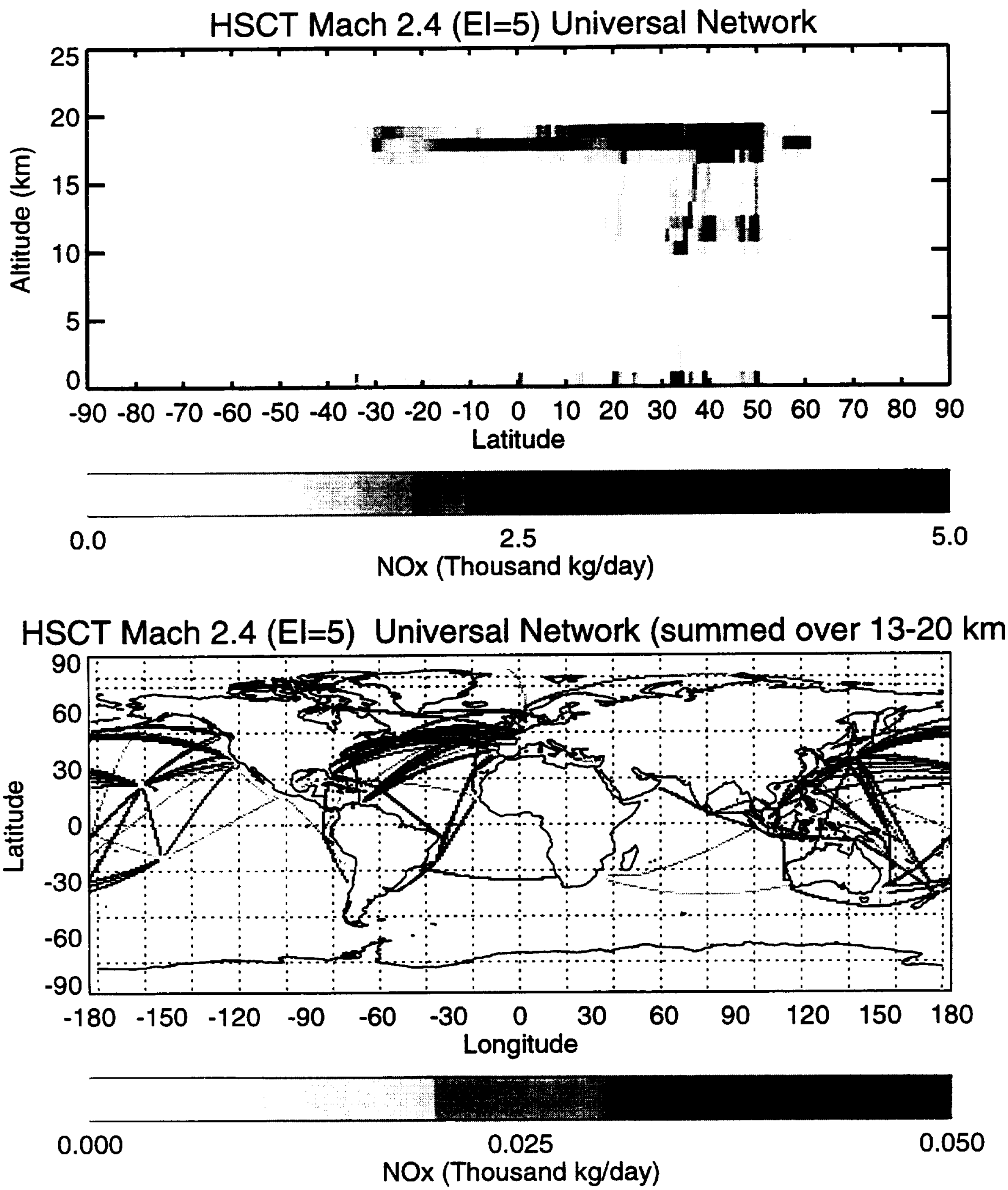


Figure 3-1. NOx emissions for a Mach 2.4 HSCT (TCA) fleet on the Universal Airline Network as a function of altitude and latitude (summed over longitude) (top panel) and as a function of latitude and longitude (summed over altitude) (bottom panel) (Values greater than maximum are plotted as black.)

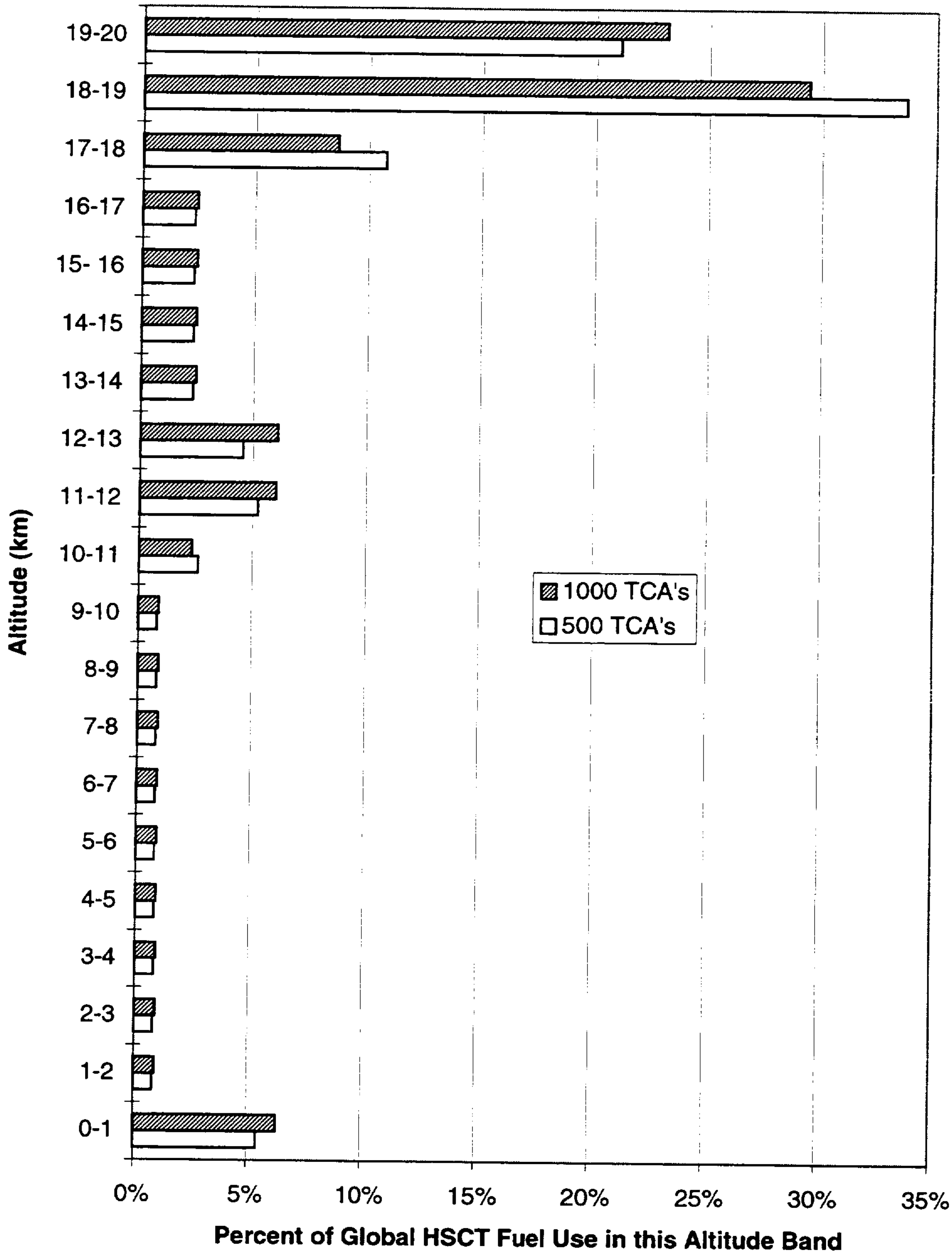


**Figure 3-2.** Distribution of TCA fuel use as a function of altitude for fleets of 500 and 1000 active TCAs.

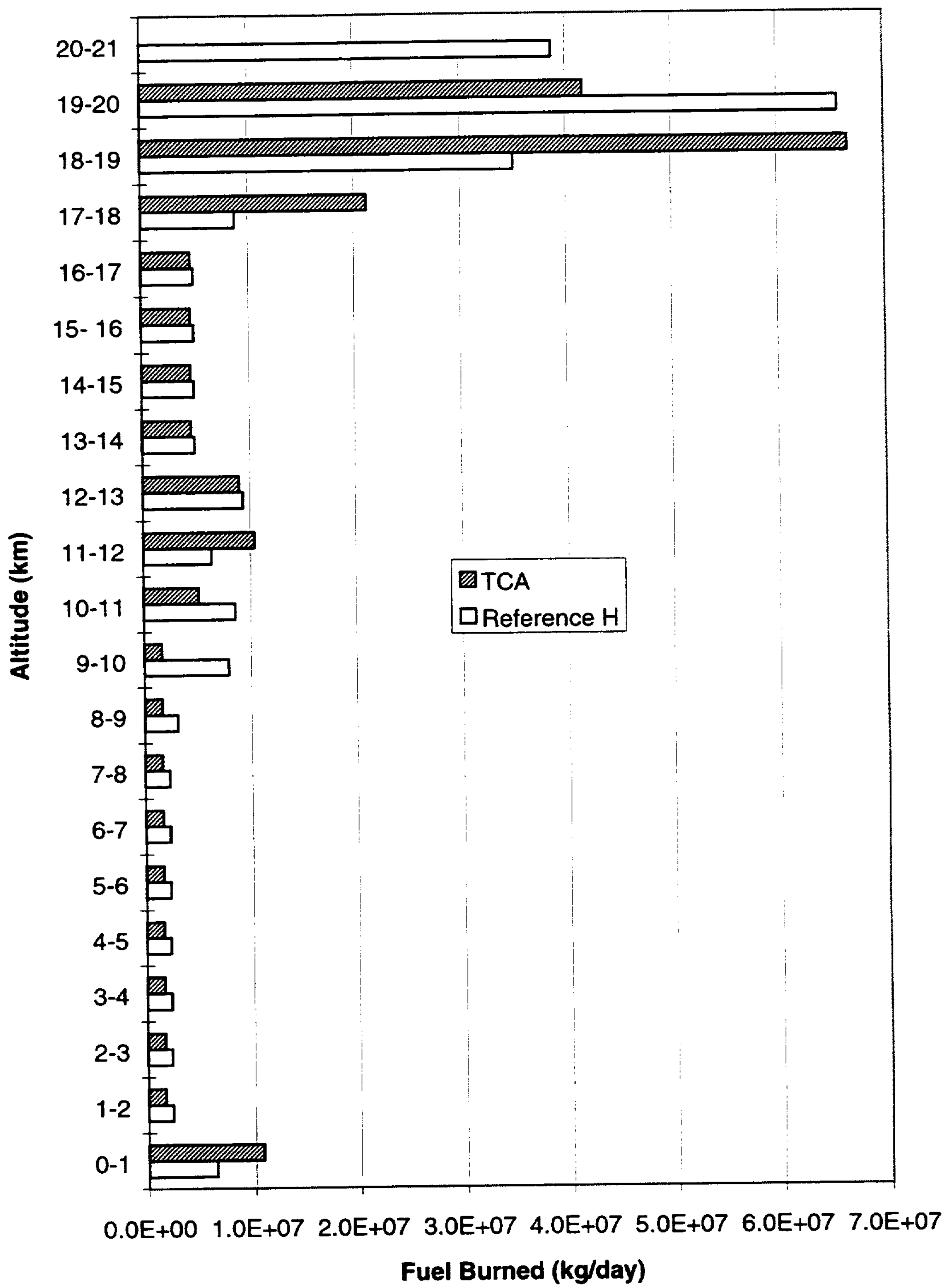


**Figure 3-3.** Comparison of the altitude distribution of the TCA with that of the Reference H HSCT used in previous HSCT scenario calculations.

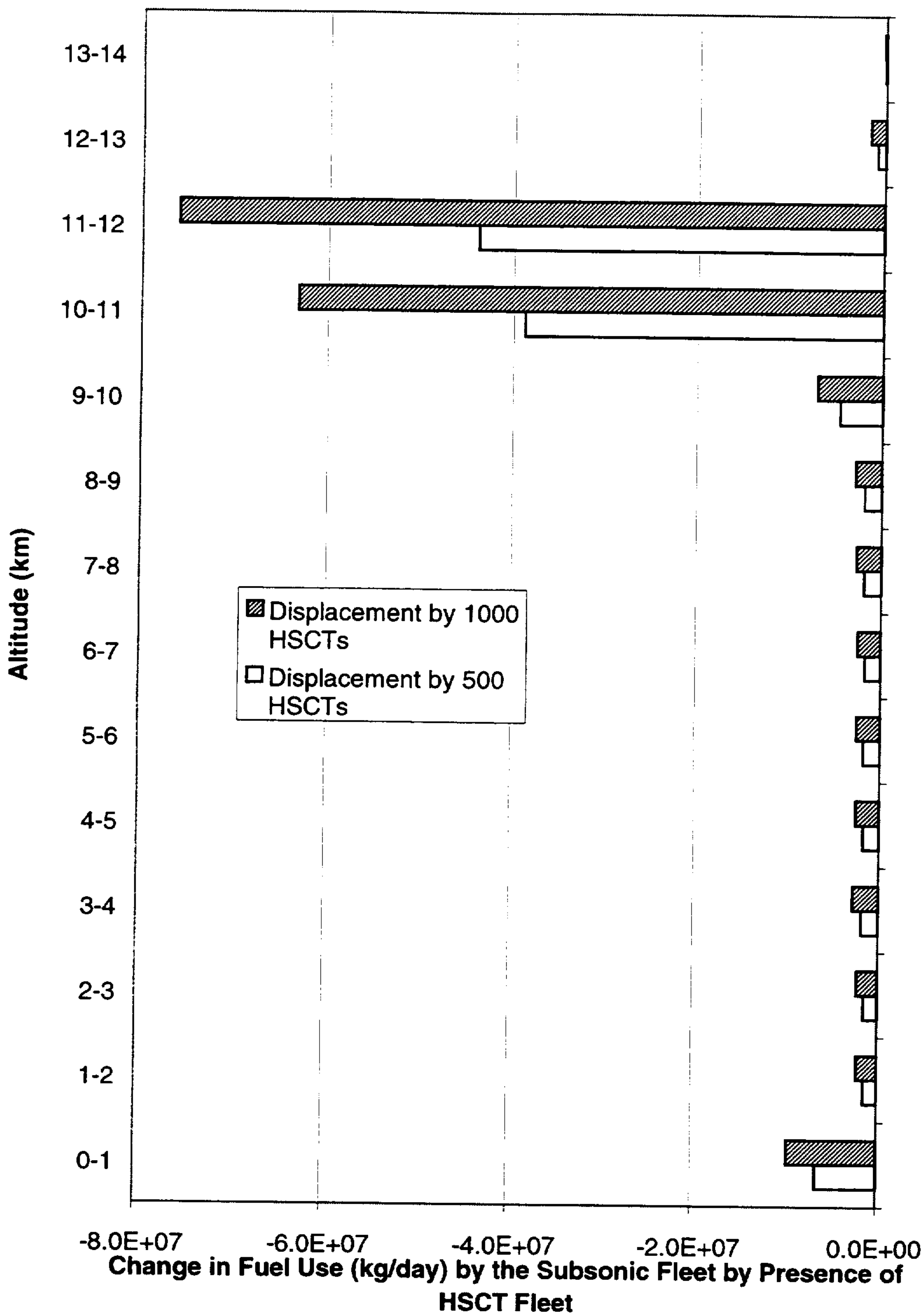


**Figure 3-4.** Calculated change in fuel use by the 2015 subsonic fleet as a function of altitude due to the presence of 500 and 1000 active TCAs.

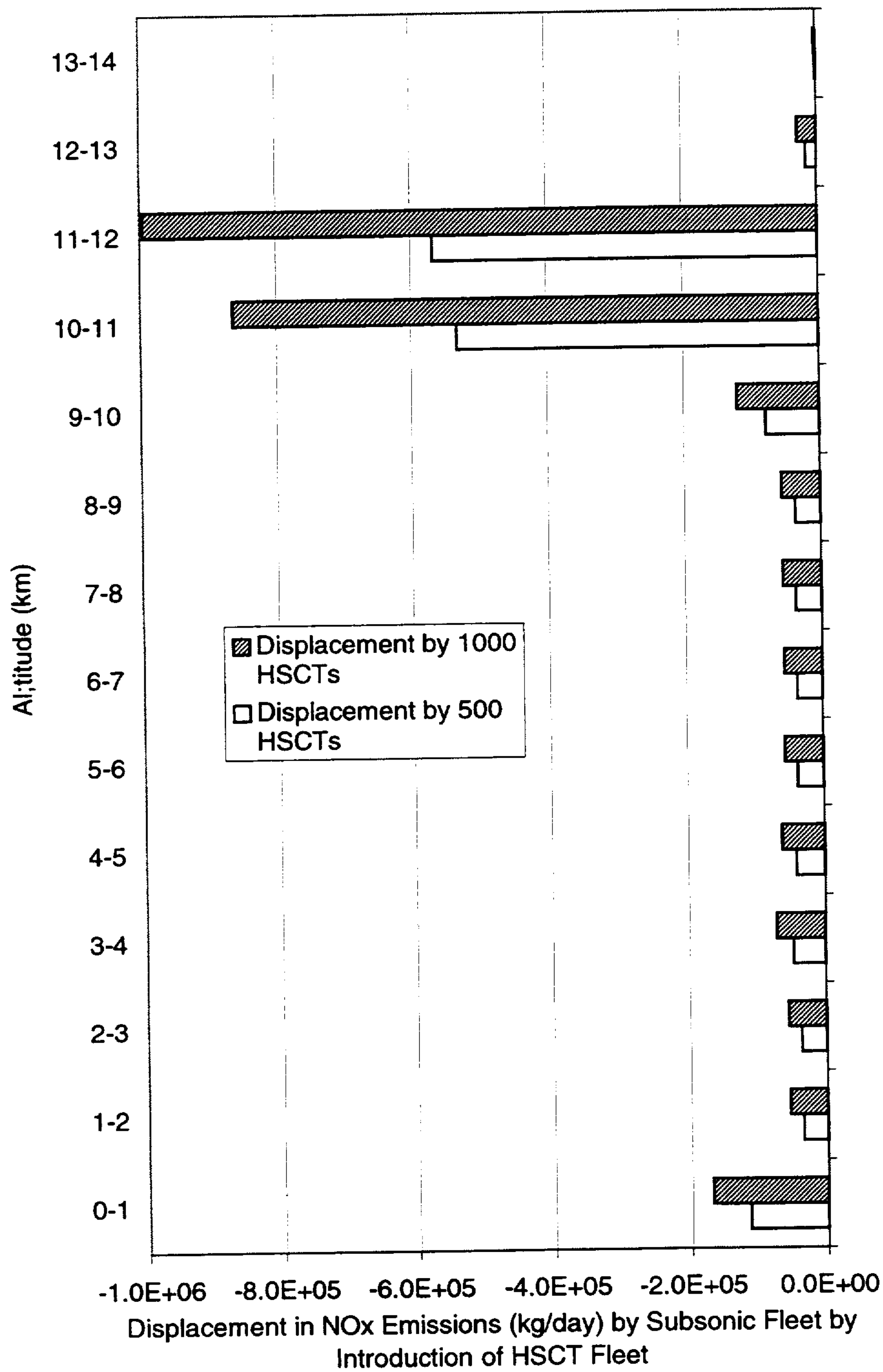


**Figure 3-5.** Calculated change in NOx emissions by the 2015 subsonic fleet as a function of altitude due to the presence of 500 and 1000 active TCAs.

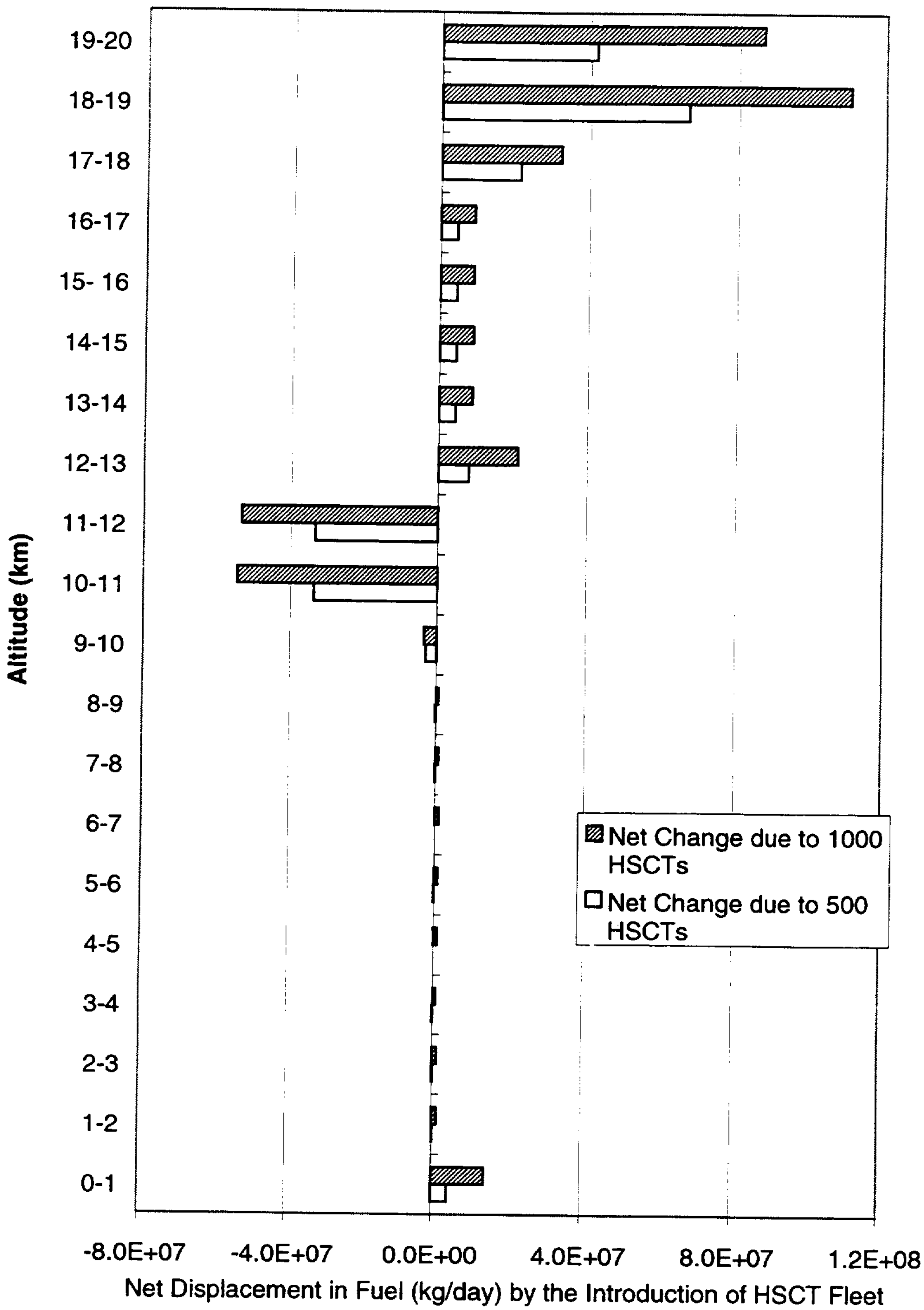


**Figure 3-6.** Net change in fuel use as a function of altitude due to the introduction of fleets of 500 and 1000 active TCAs.

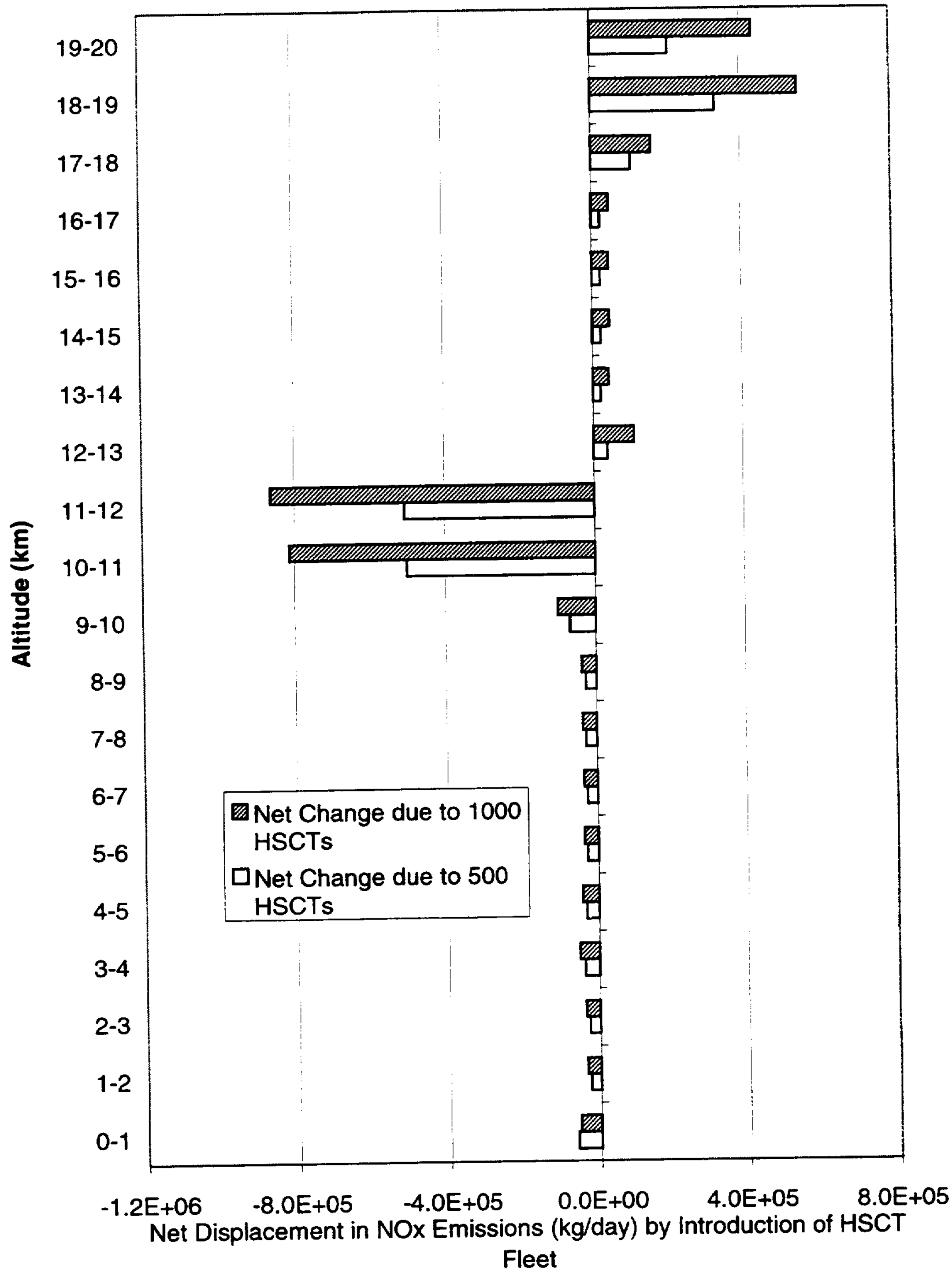


**Figure 3-7.** Net change in NOx emissions as a function of altitude due to the introduction of fleets of 500 and 1000 active TCAs with EI(NOx)=5 combustors.

## 4. Conclusions

Emission scenarios for fleets of approximately 500 and 1000 high speed civil transports have been calculated on a universal airline network using the NASA technology concept airplane (TCA) performance and emissions characteristics (EI(NOx)=5 at supersonic cruise). Fuel burned and emissions (NOx, hydrocarbons, and carbon monoxide) were calculated onto a 1 degree latitude x 1 degree longitude x 1 kilometer pressure altitude grid and delivered electronically to NASA Langley Research Center. In addition, the displacement in emissions from subsonic aircraft by the utilization of the HSCTs was calculated based on the year 2015 subsonic emission scenario reported elsewhere (Baughcum, *et al.*, 1998).

Global jet fuel use by fleets of 500 and 1000 active TCA HSCTs was calculated to be 198 and 375 million kilograms/day, respectively. This is approximately 12% less global fuel use for the TCA, compared to the Reference H HSCT model used in earlier HSCT scenario calculations (Baughcum and Henderson, 1995). The TCA is calculated to burn approximately 13 % less fuel above 17 kilometers altitudes than did the Reference H aircraft used in the scenarios for the 1995 AESA assessment (Stolarski, *et al.*, 1995). Assuming the same combustor technology in both, this is about 13% less NOx injected at altitudes above 17 kilometers. Supersonic cruising climb for the TCA occurs approximately 1 kilometer lower than for the Reference H HSCT used in previous HSCT scenario calculations.

The net effect on global fuel use by scheduled air traffic by the introduction of fleets of 500 and 1000 HSCTs, was an increase of 90 and 198 million kilograms/day, respectively, assuming year 2015 technology and accounting for the displacement of subsonic aircraft by HSCTs. Assuming EI(NOx)=5 combustor technology for the TCA, global NOx emissions from aircraft were calculated to decrease by 0.6 and 0.7 million kilograms/day for fleets of 500 and 1000 HSCTs, respectively. The displacement of emissions from the subsonic fleet by a supersonic fleet resulted in lower tropospheric NOx emissions relative to the all subsonic case.

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

## 5. References


Albritton, D. L., W. H. Brune, A. R. Douglass, F. L. Dryer, M. K. W. Ko, C. E. Kolb, R. C. Miake-Lye, M. J. Prather, A. R. Ravishankara, R. B. Rood, R. S. Stolarski, R. T. Watson, and D. J. Wuebbles, *The Atmospheric Effects of Stratospheric Aircraft: Interim Assessment Report of the NASA High-Speed Research Program*, NASA Reference Publication 1333, 1993.

Baughcum, S. L., S. C. Henderson, P. S. Hertel, D. R. Maggiora, and C. A. Oncina, *Stratospheric Emissions Effects Database Development,* NASA CR-4592, 1994.

Baughcum, S. L., and S. C. Henderson, *Aircraft Emission Inventories Projected in Year 2015 for a High Speed Civil Transport (HSCT) Universal Airline Network*, NASA CR-4659, 1995.

Baughcum, S. L. , T. G. Tritz, S. C. Henderson, and D. C. Pickett, *Scheduled Civil Aircraft Emission Inventories for 1992: Database Development and Analysis*, NASA CR-4700, 1996.

Baughcum, S. L., D. J. Sutkus, and S. C. Henderson, *Year 2015 Aircraft Emission Scenario for Scheduled Air Traffic*, NASA/CR-1998-207638, 1998.

Landau, Z. H., M. Metwally, R. Van Alstyne, and C. A. Ward, *Jet Aircraft Engine Exhaust Emissions Database Development -- Year 1990 and 2015 Scenarios*, NASA CR-4613, 1994.

Metwally, M., *High-Speed Civil Transport Forecast: Simulated Airline Scenarios for Mach 1.6, Mach 2.0, and Mach 2.4 Configurations for Year 2015*, NASA CR-4710, 1996.

A. Mortlock and R. van Alstyne, *Military, Charter, Unreported Domestic Traffic and General Aviation 1976, 1984, 1992, and 2015 Emission Scenarios*, NASA/CR-1998-207639, 1998.

Stolarski, R. S., and H. L. Wesoky (eds.), *The Atmospheric Effects of Stratospheric Aircraft: A Third Program Report*, NASA Reference Publication 1313, 1993.

Stolarski, R. S., S. L. Baughcum, W. H. Brune, A. R. Douglass, D. W. Fahey, R. R. Friedl, S. C. Liu, R. A. Plumb, L. R. Poole, H. L. Wesoky, and D. R. Worsnop, *1995 Scientific Assessment of the Atmospheric Effects of Stratospheric Aircraft*, NASA Reference Publication 1381, 1995.

Wuebbles, D. J., D. Maiden, R. K. Seals, Jr., S. L. Baughcum, M. Metwally, and A. Mortlock, "Emissions Scenarios Development: Report of the Emissions Scenarios Committee," in *The Atmospheric Effects of Stratospheric Aircraft: A Third Program Report*, R. S. Stolarski and H. L. Wesoky, eds., NASA Reference Publication 1313, 1993.

## Appendix A. Fuel Burned and Emissions as a Function of Altitude

**Table A-1.** 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 a fleet of 500 TCA HSCTs with EI(NOx)=5 grams NOx (as $NO_2$) per kilogram of fuel burned.

| 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 | 1.07E+07 | 5.4% | 5.17E+04 | 5.1% | 3.21E+03 | 5.6% | 3.08E+04 | 5.4% | 4.8 | 0.3 | 2.9 |
| 1 - 2 | 1.64E+06 | 6.3% | 8.73E+03 | 6.0% | 4.80E+02 | 6.4% | 4.71E+03 | 6.3% | 5.3 | 0.3 | 2.9 |
| 2 - 3 | 1.64E+06 | 7.1% | 8.73E+03 | 6.8% | 4.80E+02 | 7.2% | 4.71E+03 | 7.1% | 5.3 | 0.3 | 2.9 |
| 3 - 4 | 1.64E+06 | 7.9% | 8.73E+03 | 7.7% | 4.80E+02 | 8.1% | 4.71E+03 | 7.9% | 5.3 | 0.3 | 2.9 |
| 4 - 5 | 1.64E+06 | 8.8% | 8.73E+03 | 8.6% | 4.80E+02 | 8.9% | 4.71E+03 | 8.8% | 5.3 | 0.3 | 2.9 |
| 5 - 6 | 1.64E+06 | 9.6% | 8.73E+03 | 9.4% | 4.80E+02 | 9.8% | 4.71E+03 | 9.6% | 5.3 | 0.3 | 2.9 |
| 6 - 7 | 1.64E+06 | 10.4% | 8.73E+03 | 10.3% | 4.80E+02 | 10.6% | 4.71E+03 | 10.4% | 5.3 | 0.3 | 2.9 |
| 7 - 8 | 1.64E+06 | 11.2% | 8.73E+03 | 11.2% | 4.80E+02 | 11.4% | 4.71E+03 | 11.3% | 5.3 | 0.3 | 2.9 |
| 8 - 9 | 1.64E+06 | 12.1% | 8.73E+03 | 12.0% | 4.80E+02 | 12.3% | 4.71E+03 | 12.1% | 5.3 | 0.3 | 2.9 |
| 9 - 10 | 1.64E+06 | 12.9% | 8.73E+03 | 12.9% | 4.80E+02 | 13.1% | 4.71E+03 | 12.9% | 5.3 | 0.3 | 2.9 |
| 10 - 11 | 5.14E+06 | 15.5% | 3.00E+04 | 15.8% | 1.50E+03 | 15.7% | 1.47E+04 | 15.5% | 5.8 | 0.3 | 2.9 |
| 11 - 12 | 1.04E+07 | 20.8% | 6.08E+04 | 21.8% | 3.02E+03 | 20.9% | 2.98E+04 | 20.8% | 5.9 | 0.3 | 2.9 |
| 12 - 13 | 8.97E+06 | 25.3% | 5.29E+04 | 27.1% | 2.61E+03 | 25.5% | 2.58E+04 | 25.3% | 5.9 | 0.3 | 2.9 |
| 13 - 14 | 4.54E+06 | 27.6% | 2.27E+04 | 29.3% | 1.33E+03 | 27.8% | 1.30E+04 | 27.6% | 5.0 | 0.3 | 2.9 |
| 14 - 15 | 4.54E+06 | 29.9% | 2.27E+04 | 31.6% | 1.33E+03 | 30.1% | 1.30E+04 | 29.9% | 5.0 | 0.3 | 2.9 |
| 15 - 16 | 4.54E+06 | 32.2% | 2.27E+04 | 33.8% | 1.33E+03 | 32.4% | 1.30E+04 | 32.2% | 5.0 | 0.3 | 2.9 |
| 16 - 17 | 4.58E+06 | 34.5% | 2.29E+04 | 36.1% | 1.34E+03 | 34.7% | 1.32E+04 | 34.5% | 5.0 | 0.3 | 2.9 |
| 17 - 18 | 2.12E+07 | 45.2% | 1.06E+05 | 46.5% | 6.17E+03 | 45.4% | 6.09E+04 | 45.2% | 5.0 | 0.3 | 2.9 |
| 18 - 19 | 6.66E+07 | 78.9% | 3.33E+05 | 79.4% | 1.93E+04 | 79.0% | 1.91E+05 | 78.9% | 5.0 | 0.3 | 2.9 |
| 19 - 20 | 4.16E+07 | 100.0% | 2.08E+05 | 100.0% | 1.21E+04 | 100.0% | 1.20E+05 | 100.0% | 5.0 | 0.3 | 2.9 |
| **Global Total** | **1.98E+08** | | **1.01E+06** | | **5.76E+04** | | **5.67E+05** | | **5.1** | **0.3** | **2.9** |

**Table A-2.** 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 a fleet of 1000 TCA HSCTs with EI(NOx)=5 grams NOx (as $NO_2$) per kilogram of fuel burned.

| 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 | 2.37E+07 | 6.3% | 1.14E+05 | 5.9% | 7.08E+03 | 6.5% | 6.79E+04 | 6.3% | 4.8 | 0.3 | 2.9 |
| 1 - 2 | 3.46E+06 | 7.2% | 1.84E+04 | 6.9% | 1.01E+03 | 7.4% | 9.94E+03 | 7.2% | 5.3 | 0.3 | 2.9 |
| 2 - 3 | 3.47E+06 | 8.2% | 1.84E+04 | 7.8% | 1.01E+03 | 8.3% | 9.95E+03 | 8.2% | 5.3 | 0.3 | 2.9 |
| 3 - 4 | 3.47E+06 | 9.1% | 1.85E+04 | 8.8% | 1.02E+03 | 9.3% | 9.97E+03 | 9.1% | 5.3 | 0.3 | 2.9 |
| 4 - 5 | 3.47E+06 | 10.0% | 1.85E+04 | 9.7% | 1.02E+03 | 10.2% | 9.97E+03 | 10.0% | 5.3 | 0.3 | 2.9 |
| 5 - 6 | 3.47E+06 | 10.9% | 1.85E+04 | 10.7% | 1.02E+03 | 11.1% | 9.97E+03 | 10.9% | 5.3 | 0.3 | 2.9 |
| 6 - 7 | 3.47E+06 | 11.9% | 1.85E+04 | 11.6% | 1.02E+03 | 12.0% | 9.97E+03 | 11.9% | 5.3 | 0.3 | 2.9 |
| 7 - 8 | 3.47E+06 | 12.8% | 1.85E+04 | 12.6% | 1.02E+03 | 13.0% | 9.97E+03 | 12.8% | 5.3 | 0.3 | 2.9 |
| 8 - 9 | 3.47E+06 | 13.7% | 1.85E+04 | 13.5% | 1.02E+03 | 13.9% | 9.97E+03 | 13.7% | 5.3 | 0.3 | 2.9 |
| 9 - 10 | 3.47E+06 | 14.6% | 1.85E+04 | 14.5% | 1.02E+03 | 14.8% | 9.97E+03 | 14.6% | 5.3 | 0.3 | 2.9 |
| 10 - 11 | 8.75E+06 | 17.0% | 5.08E+04 | 17.1% | 2.55E+03 | 17.2% | 2.51E+04 | 17.0% | 5.8 | 0.3 | 2.9 |
| 11 - 12 | 2.27E+07 | 23.0% | 1.34E+05 | 24.1% | 6.60E+03 | 23.2% | 6.51E+04 | 23.0% | 5.9 | 0.3 | 2.9 |
| 12 - 13 | 2.29E+07 | 29.1% | 1.36E+05 | 31.1% | 6.66E+03 | 29.3% | 6.57E+04 | 29.1% | 6.0 | 0.3 | 2.9 |
| 13 - 14 | 9.12E+06 | 31.5% | 4.56E+04 | 33.5% | 2.67E+03 | 31.7% | 2.62E+04 | 31.5% | 5.0 | 0.3 | 2.9 |
| 14 - 15 | 9.12E+06 | 34.0% | 4.56E+04 | 35.8% | 2.67E+03 | 34.2% | 2.62E+04 | 34.0% | 5.0 | 0.3 | 2.9 |
| 15 - 16 | 9.12E+06 | 36.4% | 4.56E+04 | 38.2% | 2.67E+03 | 36.6% | 2.62E+04 | 36.4% | 5.0 | 0.3 | 2.9 |
| 16 - 17 | 9.20E+06 | 38.9% | 4.60E+04 | 40.6% | 2.69E+03 | 39.1% | 2.64E+04 | 38.9% | 5.0 | 0.3 | 2.9 |
| 17 - 18 | 3.23E+07 | 47.5% | 1.62E+05 | 49.0% | 9.40E+03 | 47.7% | 9.28E+04 | 47.5% | 5.0 | 0.3 | 2.9 |
| 18 - 19 | 1.10E+08 | 76.9% | 5.52E+05 | 77.5% | 3.20E+04 | 77.0% | 3.17E+05 | 76.9% | 5.0 | 0.3 | 2.9 |
| 19 - 20 | 8.67E+07 | 100.0% | 4.34E+05 | 100.0% | 2.52E+04 | 100.0% | 2.49E+05 | 100.0% | 5.0 | 0.3 | 2.9 |
| **Global Total** | **3.75E+08** | | **1.93E+06** | | **1.09E+05** | | **1.08E+06** | | **5.1** | **0.3** | **2.9** |

**Table A-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 a fleet of 500 Reference H HSCTs with EI(NOx)=5 grams NOx (as $NO_2$) per kilogram of fuel burned.

| 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 | 6.34E+06 | 2.8% | 4.55E+04 | 3.3% | 7.92E+03 | 9.8% | 7.44E+04 | 11.3% | 7.2 | 1.2 | 11.7 |
| 1 - 2 | 2.29E+06 | 3.8% | 1.88E+04 | 4.6% | 1.28E+03 | 11.3% | 8.07E+03 | 12.5% | 8.2 | 0.6 | 3.5 |
| 2 - 3 | 2.29E+06 | 4.9% | 1.88E+04 | 6.0% | 1.28E+03 | 12.9% | 8.07E+03 | 13.7% | 8.2 | 0.6 | 3.5 |
| 3 - 4 | 2.29E+06 | 5.9% | 1.89E+04 | 7.3% | 1.28E+03 | 14.5% | 8.07E+03 | 14.9% | 8.2 | 0.6 | 3.5 |
| 4 - 5 | 2.28E+06 | 6.9% | 1.88E+04 | 8.7% | 1.28E+03 | 16.1% | 8.07E+03 | 16.1% | 8.2 | 0.6 | 3.5 |
| 5 - 6 | 2.29E+06 | 7.9% | 1.88E+04 | 10.0% | 1.28E+03 | 17.6% | 8.07E+03 | 17.4% | 8.2 | 0.6 | 3.5 |
| 6 - 7 | 2.29E+06 | 8.9% | 1.88E+04 | 11.4% | 1.28E+03 | 19.2% | 8.07E+03 | 18.6% | 8.2 | 0.6 | 3.5 |
| 7 - 8 | 2.29E+06 | 9.9% | 1.89E+04 | 12.7% | 1.28E+03 | 20.8% | 8.07E+03 | 19.8% | 8.2 | 0.6 | 3.5 |
| 8 - 9 | 3.06E+06 | 11.3% | 2.53E+04 | 14.5% | 1.63E+03 | 22.8% | 1.16E+04 | 21.6% | 8.3 | 0.5 | 3.8 |
| 9 - 10 | 7.86E+06 | 14.8% | 6.54E+04 | 19.2% | 3.64E+03 | 27.3% | 2.96E+04 | 26.0% | 8.3 | 0.5 | 3.8 |
| 10 - 11 | 8.53E+06 | 18.6% | 7.13E+04 | 24.3% | 3.73E+03 | 31.9% | 2.73E+04 | 30.2% | 8.4 | 0.4 | 3.2 |
| 11 - 12 | 6.31E+06 | 21.4% | 5.32E+04 | 28.1% | 2.63E+03 | 35.1% | 1.44E+04 | 32.3% | 8.4 | 0.4 | 2.3 |
| 12 - 13 | 9.33E+06 | 25.5% | 7.87E+04 | 33.7% | 3.73E+03 | 39.7% | 2.50E+04 | 36.1% | 8.4 | 0.4 | 2.7 |
| 13 - 14 | 4.85E+06 | 27.7% | 4.18E+04 | 36.7% | 1.52E+03 | 41.6% | 2.95E+03 | 36.6% | 8.6 | 0.3 | 0.6 |
| 14 - 15 | 4.85E+06 | 29.8% | 4.18E+04 | 39.7% | 1.52E+03 | 43.4% | 2.96E+03 | 37.0% | 8.6 | 0.3 | 0.6 |
| 15 - 16 | 4.85E+06 | 32.0% | 4.18E+04 | 42.7% | 1.52E+03 | 45.3% | 2.96E+03 | 37.5% | 8.6 | 0.3 | 0.6 |
| 16 - 17 | 4.85E+06 | 34.2% | 4.18E+04 | 45.7% | 1.52E+03 | 47.2% | 2.96E+03 | 37.9% | 8.6 | 0.3 | 0.6 |
| 17 - 18 | 8.75E+06 | 38.0% | 6.17E+04 | 50.1% | 2.64E+03 | 50.4% | 1.51E+04 | 40.2% | 7.1 | 0.3 | 1.7 |
| 18 - 19 | 3.50E+07 | 53.6% | 1.75E+05 | 62.7% | 1.02E+04 | 62.9% | 9.57E+04 | 54.7% | 5.0 | 0.3 | 2.7 |
| 19 - 20 | 6.56E+07 | 82.8% | 3.28E+05 | 86.1% | 1.89E+04 | 86.3% | 1.88E+05 | 83.1% | 5.0 | 0.3 | 2.9 |
| 20 - 21` | 3.87E+07 | 100.0% | 1.94E+05 | 100.0% | 1.12E+04 | 100.0% | 1.12E+05 | 100.0% | 5.0 | 0.3 | 2.9 |
| **Global** | **2.25E+08** | | **1.40E+06** | | **8.13E+04** | | **6.61E+05** | | **6.2** | **0.4** | **2.9** |

**Table A-4.** 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 the 2015 subsonic fleet assuming no HSCT fleet.

| 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** |

**Table A-5.** 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 a 2015 subsonic fleet accounting for the displacement by 500 HSCTs.

| 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 | 5.91E+07 | 10.3% | 7.76E+05 | 9.6% | 1.39E+05 | 32.2% | 9.85E+05 | 35.6% | 13.1 | 2.3 | 16.7 |
| 1 - 2 | 1.58E+07 | 13.0% | 2.80E+05 | 13.1% | 2.73E+04 | 38.5% | 1.72E+05 | 41.8% | 17.8 | 1.7 | 10.9 |
| 2 - 3 | 1.48E+07 | 15.6% | 2.71E+05 | 16.5% | 2.47E+04 | 44.3% | 1.51E+05 | 47.3% | 18.3 | 1.7 | 10.2 |
| 3 - 4 | 1.74E+07 | 18.6% | 3.29E+05 | 20.6% | 2.38E+04 | 49.8% | 1.41E+05 | 52.3% | 18.9 | 1.4 | 8.1 |
| 4 - 5 | 1.61E+07 | 21.4% | 2.90E+05 | 24.2% | 2.37E+04 | 55.3% | 1.40E+05 | 57.4% | 18.0 | 1.5 | 8.7 |
| 5 - 6 | 1.58E+07 | 24.1% | 2.67E+05 | 27.5% | 2.33E+04 | 60.7% | 1.38E+05 | 62.4% | 16.9 | 1.5 | 8.7 |
| 6 - 7 | 1.64E+07 | 27.0% | 2.71E+05 | 30.8% | 2.27E+04 | 66.0% | 1.29E+05 | 67.0% | 16.5 | 1.4 | 7.8 |
| 7 - 8 | 1.69E+07 | 29.9% | 2.67E+05 | 34.1% | 2.29E+04 | 71.3% | 1.26E+05 | 71.6% | 15.8 | 1.4 | 7.5 |
| 8 - 9 | 1.80E+07 | 33.0% | 2.75E+05 | 37.5% | 2.12E+04 | 76.2% | 1.16E+05 | 75.8% | 15.3 | 1.2 | 6.5 |
| 9 - 10 | 6.32E+07 | 44.0% | 8.96E+05 | 48.7% | 2.96E+04 | 83.1% | 1.81E+05 | 82.3% | 14.2 | 0.5 | 2.9 |
| 10 - 11 | 1.77E+08 | 74.7% | 2.29E+06 | 77.1% | 4.62E+04 | 93.8% | 3.09E+05 | 93.5% | 13.0 | 0.3 | 1.7 |
| 11 - 12 | 1.42E+08 | 99.3% | 1.79E+06 | 99.3% | 2.59E+04 | 99.8% | 1.77E+05 | 99.9% | 12.6 | 0.2 | 1.2 |
| 12 - 13 | 3.53E+06 | 100.0% | 5.43E+04 | 99.9% | 6.18E+02 | 100.0% | 3.42E+03 | 100.0% | 15.4 | 0.2 | 1.0 |
| 13 - 14 | 3.12E+05 | 100.0% | 5.41E+03 | 100.0% | 7.75E+01 | 100.0% | 2.78E+02 | 100.0% | 17.3 | 0.2 | 0.9 |
| **Global Total** | **5.76E+08** | | **8.06E+06** | | **4.31E+05** | | **2.77E+06** | | **14.0** | **0.7** | **4.8** |

**Table A-6.** 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 a 2015 subsonic fleet accounting for the displacement by 1000 HSCTs.

| 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 | 5.60E+07 | 11.1% | 7.20E+05 | 10.3% | 1.32E+05 | 32.7% | 9.42E+05 | 36.1% | 12.9 | 2.4 | 16.8 |
| 1 - 2 | 1.50E+07 | 14.0% | 2.62E+05 | 14.0% | 2.61E+04 | 39.1% | 1.66E+05 | 42.4% | 17.4 | 1.7 | 11.0 |
| 2 - 3 | 1.40E+07 | 16.8% | 2.52E+05 | 17.6% | 2.35E+04 | 44.9% | 1.44E+05 | 47.9% | 18.0 | 1.7 | 10.3 |
| 3 - 4 | 1.65E+07 | 20.1% | 3.05E+05 | 21.9% | 2.25E+04 | 50.4% | 1.34E+05 | 53.1% | 18.5 | 1.4 | 8.2 |
| 4 - 5 | 1.53E+07 | 23.1% | 2.69E+05 | 25.7% | 2.26E+04 | 56.0% | 1.34E+05 | 58.2% | 17.6 | 1.5 | 8.8 |
| 5 - 6 | 1.50E+07 | 26.1% | 2.49E+05 | 29.3% | 2.22E+04 | 61.5% | 1.32E+05 | 63.3% | 16.5 | 1.5 | 8.8 |
| 6 - 7 | 1.56E+07 | 29.1% | 2.52E+05 | 32.9% | 2.17E+04 | 66.8% | 1.23E+05 | 68.0% | 16.1 | 1.4 | 7.9 |
| 7 - 8 | 1.60E+07 | 32.3% | 2.48E+05 | 36.4% | 2.17E+04 | 72.2% | 1.21E+05 | 72.6% | 15.5 | 1.4 | 7.5 |
| 8 - 9 | 1.70E+07 | 35.7% | 2.54E+05 | 40.0% | 2.00E+04 | 77.1% | 1.11E+05 | 76.8% | 14.9 | 1.2 | 6.5 |
| 9 - 10 | 6.08E+07 | 47.7% | 8.54E+05 | 52.2% | 2.82E+04 | 84.1% | 1.74E+05 | 83.5% | 14.1 | 0.5 | 2.9 |
| 10 - 11 | 1.52E+08 | 77.7% | 1.96E+06 | 80.0% | 4.28E+04 | 94.6% | 2.85E+05 | 94.4% | 12.9 | 0.3 | 1.9 |
| 11 - 12 | 1.10E+08 | 99.4% | 1.36E+06 | 99.4% | 2.14E+04 | 99.9% | 1.43E+05 | 99.9% | 12.4 | 0.2 | 1.3 |
| 12 - 13 | 2.77E+06 | 100.0% | 4.16E+04 | 99.9% | 4.48E+02 | 100.0% | 2.70E+03 | 100.0% | 15.0 | 0.2 | 1.0 |
| 13 - 14 | 2.48E+05 | 100.0% | 4.22E+03 | 100.0% | 5.74E+01 | 100.0% | 2.18E+02 | 100.0% | 17.0 | 0.2 | 0.9 |
| **Global Total** | **5.06E+08** | | **7.03E+06** | | **4.06E+05** | | **2.61E+06** | | **13.9** | **0.8** | **5.2** |

**Table A-7**. 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 the calculated displacement of subsonic aircraft by a fleet of 500 active HSCTs.

| Altitude Band (km) | Fuel (kg/day) | NOx (kg/day) | HC (kg/day) | CO (kg/day) |
|---|---|---|---|---|
| 0 - 1 | -6.53E+06 | -1.14E+05 | -1.22E+04 | -9.43E+04 |
| 1 - 2 | -1.45E+06 | -3.53E+04 | -2.31E+03 | -1.57E+04 |
| 2 - 3 | -1.48E+06 | -3.65E+04 | -2.26E+03 | -1.47E+04 |
| 3 - 4 | -1.81E+06 | -4.71E+04 | -2.32E+03 | -1.43E+04 |
| 4 - 5 | -1.68E+06 | -4.16E+04 | -2.25E+03 | -1.44E+04 |
| 5 - 6 | -1.78E+06 | -3.81E+04 | -2.13E+03 | -1.36E+04 |
| 6 - 7 | -1.65E+06 | -3.68E+04 | -1.98E+03 | -1.22E+04 |
| 7 - 8 | -1.83E+06 | -3.76E+04 | -2.01E+03 | -1.18E+04 |
| 8 - 9 | -1.83E+06 | -3.69E+04 | -1.82E+03 | -1.05E+04 |
| 9 - 10 | -4.55E+06 | -7.88E+04 | -2.09E+03 | -1.14E+04 |
| 10 - 11 | -3.88E+07 | -5.32E+05 | -4.85E+03 | -3.71E+04 |
| 11 - 12 | -4.38E+07 | -5.67E+05 | -5.11E+03 | -4.24E+04 |
| 12 - 13 | -8.52E+05 | -1.54E+04 | -2.29E+02 | -8.14E+02 |
| 13 - 14 | -6.80E+04 | -1.28E+03 | -2.19E+01 | -6.34E+01 |
| **Global Total** | **-1.08E+08** | **-1.62E+06** | **-4.16E+04** | **-2.93E+05** |

**Table A-8.** 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 the displacement of subsonic emissions by a fleet of 1000 active HSCTs.

| Altitude Band (km) | Fuel (kg/day) | NOx (kg/day) | HC (kg/day) | CO (kg/day) |
|---|---|---|---|---|
| 0 - 1 | -9.60E+06 | -1.69E+05 | -1.84E+04 | -1.37E+05 |
| 1 - 2 | -2.19E+06 | -5.37E+04 | -3.53E+03 | -2.24E+04 |
| 2 - 3 | -2.23E+06 | -5.51E+04 | -3.53E+03 | -2.15E+04 |
| 3 - 4 | -2.73E+06 | -7.12E+04 | -3.59E+03 | -2.06E+04 |
| 4 - 5 | -2.50E+06 | -6.25E+04 | -3.42E+03 | -2.05E+04 |
| 5 - 6 | -2.54E+06 | -5.63E+04 | -3.24E+03 | -1.94E+04 |
| 6 - 7 | -2.46E+06 | -5.57E+04 | -3.03E+03 | -1.76E+04 |
| 7 - 8 | -2.67E+06 | -5.65E+04 | -3.12E+03 | -1.72E+04 |
| 8 - 9 | -2.79E+06 | -5.75E+04 | -2.93E+03 | -1.57E+04 |
| 9 - 10 | -6.96E+06 | -1.21E+05 | -3.46E+03 | -1.75E+04 |
| 10 - 11 | -6.32E+07 | -8.64E+05 | -8.22E+03 | -6.14E+04 |
| 11 - 12 | -7.61E+07 | -9.95E+05 | -9.63E+03 | -7.63E+04 |
| 12 - 13 | -1.61E+06 | -2.81E+04 | -3.99E+02 | -1.53E+03 |
| 13 - 14 | -1.32E+05 | -2.47E+03 | -4.20E+01 | -1.24E+02 |
| **Global Total** | **-1.78E+08** | **-2.65E+06** | **-6.66E+04** | **-4.49E+05** |

**Table A-9.** 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 the net change in emissions of a 2015 fleet with 500 HSCTs compared to the all subsonic fleet.

| Altitude Band (km) | Fuel (kg/day) | NOx (kg/day) | HC (kg/day) | CO (kg/day) |
|---|---|---|---|---|
| 0 - 1 | 4.20E+06 | -6.19E+04 | -8.98E+03 | -6.35E+04 |
| 1 - 2 | 1.88E+05 | -2.66E+04 | -1.83E+03 | -1.10E+04 |
| 2 - 3 | 1.63E+05 | -2.77E+04 | -1.78E+03 | -1.00E+04 |
| 3 - 4 | -1.70E+05 | -3.83E+04 | -1.84E+03 | -9.58E+03 |
| 4 - 5 | -3.40E+04 | -3.29E+04 | -1.77E+03 | -9.64E+03 |
| 5 - 6 | -1.37E+05 | -2.94E+04 | -1.65E+03 | -8.91E+03 |
| 6 - 7 | -9.34E+03 | -2.80E+04 | -1.50E+03 | -7.47E+03 |
| 7 - 8 | -1.87E+05 | -2.89E+04 | -1.53E+03 | -7.13E+03 |
| 8 - 9 | -1.88E+05 | -2.82E+04 | -1.34E+03 | -5.74E+03 |
| 9 - 10 | -2.90E+06 | -7.00E+04 | -1.61E+03 | -6.73E+03 |
| 10 - 11 | -3.36E+07 | -5.02E+05 | -3.35E+03 | -2.24E+04 |
| 11 - 12 | -3.34E+07 | -5.07E+05 | -2.09E+03 | -1.26E+04 |
| 12 - 13 | 8.12E+06 | 3.75E+04 | 2.38E+03 | 2.49E+04 |
| 13 - 14 | 4.47E+06 | 2.14E+04 | 1.31E+03 | 1.30E+04 |
| 14 - 15 | 4.54E+06 | 2.27E+04 | 1.33E+03 | 1.30E+04 |
| 15 - 16 | 4.54E+06 | 2.27E+04 | 1.33E+03 | 1.30E+04 |
| 16 - 17 | 4.58E+06 | 2.29E+04 | 1.34E+03 | 1.32E+04 |
| 17 - 18 | 2.12E+07 | 1.06E+05 | 6.17E+03 | 6.09E+04 |
| 18 - 19 | 6.66E+07 | 3.33E+05 | 1.93E+04 | 1.91E+05 |
| 19 - 20 | 4.16E+07 | 2.08E+05 | 1.21E+04 | 1.20E+05 |
| **Global Total** | **8.96E+07** | **-6.06E+05** | **1.60E+04** | **2.74E+05** |

**Table A-10.** 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 the net change in emissions due to a fleet of 1000 HSCTs compared to the 2015 all subsonic fleet.

| Altitude Band (km) | Fuel (kg/day) | NOx (kg/day) | HC (kg/day) | CO (kg/day) |
|---|---|---|---|---|
| 0 - 1 | 1.41E+07 | -5.52E+04 | -1.13E+04 | -6.92E+04 |
| 1 - 2 | 1.27E+06 | -3.53E+04 | -2.51E+03 | -1.25E+04 |
| 2 - 3 | 1.23E+06 | -3.67E+04 | -2.52E+03 | -1.16E+04 |
| 3 - 4 | 7.39E+05 | -5.28E+04 | -2.57E+03 | -1.06E+04 |
| 4 - 5 | 9.72E+05 | -4.41E+04 | -2.41E+03 | -1.05E+04 |
| 5 - 6 | 9.35E+05 | -3.79E+04 | -2.23E+03 | -9.46E+03 |
| 6 - 7 | 1.01E+06 | -3.72E+04 | -2.01E+03 | -7.67E+03 |
| 7 - 8 | 8.01E+05 | -3.81E+04 | -2.11E+03 | -7.27E+03 |
| 8 - 9 | 6.86E+05 | -3.91E+04 | -1.91E+03 | -5.72E+03 |
| 9 - 10 | -3.48E+06 | -1.03E+05 | -2.45E+03 | -7.56E+03 |
| 10 - 11 | -5.45E+07 | -8.13E+05 | -5.67E+03 | -3.63E+04 |
| 11 - 12 | -5.34E+07 | -8.61E+05 | -3.04E+03 | -1.12E+04 |
| 12 - 13 | 2.13E+07 | 1.08E+05 | 6.26E+03 | 6.42E+04 |
| 13 - 14 | 8.99E+06 | 4.31E+04 | 2.63E+03 | 2.60E+04 |
| 14 - 15 | 9.12E+06 | 4.56E+04 | 2.67E+03 | 2.62E+04 |
| 15 - 16 | 9.12E+06 | 4.56E+04 | 2.67E+03 | 2.62E+04 |
| 16 - 17 | 9.20E+06 | 4.60E+04 | 2.69E+03 | 2.64E+04 |
| 17 - 18 | 3.23E+07 | 1.62E+05 | 9.40E+03 | 9.28E+04 |
| 18 - 19 | 1.10E+08 | 5.52E+05 | 3.20E+04 | 3.17E+05 |
| 19 - 20 | 8.67E+07 | 4.34E+05 | 2.52E+04 | 2.49E+05 |
| **Global Total** | **1.98E+08** | **-7.18E+05** | **4.28E+04** | **6.28E+05** |

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This report describes the development of a three-dimensional database of aircraft fuel burn and emissions (fuel burned,NOx, CO, and hydrocarbons) from projected fleets of high speed civil transports (HSCTs) on a universal airline network. Inventories for 500 and 1000 HSCT fleets, as well as the concurrent subsonic fleets, were calculated. The HSCT scenarios are calculated using the NASA technology concept airplane (TCA) and update an earlier report (NASA CR-4659).

These emissions inventories are available for use by atmospheric scientists conducting the Atmospheric Effects of Stratospheric Aircraft (AESA) modeling studies. Fuel burned and emissions of nitrogen oxides (NOx as NO2), carbon monoxide, and hydrocarbons have been calculated on a 1 degree latitude x 1 degree longitude x 1 kilometer pressure altitude grid and delivered to NASA as electronic files.

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