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System for assessing Aviation's Global Emissions (SAGE), Part 1: Model description and inventory results

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Abstract

In early 2001, the US Federal Aviation Administration embarked on a multi-year effort to develop a new computer model, the System for assessing Aviation's Global Emissions (SAGE). Currently at Version 1.5, the basic use of the model has centered on the development of yearly global inventories of commercial aircraft fuel burn and emissions of various pollutants to serve as the basis for scenario modeling. This paper describes the algorithms and data used in the model as well as the results from initial validation assessments. SAGE results indicate that global fuel burn and nitrogen oxide (NO_x) emissions decreased by over 6% from 2000 to 2001 (fuel burn and NO_x), and then steadily increased to over 12% (fuel burn) and 15.5% (NO_x) above 2000 levels in 2005. Comparisons to the results from previous studies have shown that SAGE tends to agree more closely with fuel burn and NO_x than with CO and HC. Validation assessments have shown that SAGE can predict per flight fuel burn to within 3% on an average basis with no apparent bias, when compared to about 60,000 flight's worth of data from a major US airline and about 20,000 flight's worth of data from two major Japanese airlines.

Keywords: Aviation; Fuel burn; Atmospheric pollution; Aircraft emissions; Global emissions inventory

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1. Introduction

The development of SAGE was in part stimulated by the growth in aviation and the need for better emissions modeling capabilities on a global level. According to the Aviation and the Global Atmosphere report by the Intergovernmental Panel on Climate Change (1999), air transportation accounted for 2% of all anthropogenic carbon dioxide emissions in 1992, and 13% of the fossil fuel used for transportation. In a 10-year period, passenger traffic on scheduled airlines grew by 60%; and air travel was expected to increase by 5% per year for the next 10–15 years. It was also estimated that in 1992, aircraft were responsible for 3.5% of all anthropogenic radiative forcing of the climate and are expected to grow to as much as 12% by 2050.

The Committee on Aviation Environmental Protection (CAEP) of the International Civil Aviation Organization (ICAO), an organization of the UN, formed several working groups to address aviation environmental emissions. In addition, the UN Framework Convention on Climate Change (UNFCCC) promoted a series of multilateral agreements that target values of emissions reductions for the primary industrialized nations.

Partly in response to the needs of these international bodies, many studies have been conducted, resulting in global inventories of emissions by various organizations, including the National Aeronautics and Space Administration (NASA)/Boeing (Baughcum et al., 1996a,b; Sutkus et al., 2001), Abatement of Nuisances Caused by Air Transport (ANCAT)/European Commission (EC) 2 group (Gardner, 1998), Deutsche Forschungsanstalt fur Luft- and Raumfahrt (DLR) (Schmitt and Brunner, 1997), and the Dutch Directorate-General of Civil Aviation's Aviation Emissions and Evaluation of Reduction Options Modeling System (AERO-MS) (Pulles, 2002). These inventories represent significant accomplishments. However, the data and tools used to develop these inventories were generally unsuitable for long-term CAEP use as they fell short of one or more of the following: Non-proprietary data and methods that would provide the international aviation community with a clear understanding of how the model works (i.e., no "black boxes"); a commitment by the developers to continue updating the data and methods used by the model, which are vital in the development of yearly inventories and tracking of temporal trends; and a dynamic and robust modeling environment that could be used to assess various scenarios. Because of these shortcomings and the growing need by CAEP and other organizations to accurately assess global emissions from aircraft, the US Federal Aviation Administration (FAA) developed the System for assessing Aviation's Global Emissions (SAGE).

SAGE, currently at Version 1.5, incorporates lessons learned from the past studies in modeling commercial flights on a global basis. Table 1 indicates some of the data and methods used in the past studies, and describes

Table 1
Comparison of selected data and methods in past studies to those in SAGE Version 1.5

Past studies	SAGE Version 1.5
(1) A portion (e.g., a day, week, month, etc.) of the world flight schedules and flight plans were used as a representation of all worldwide movements.	(1) All commercial flights worldwide are modeled such that there are no assumptions associated with modeling a smaller set of flights.
(2) Schedule data were used as the basis for modeling global flights with simulated trajectories.	(2) SAGE uses a mix of radar data and schedule information. The radar data takes precedence over schedule information as it provides both actual flight plans and actual trajectories. Radar data is available for North America and parts of western Europe and South America.
(3) Great Circle paths were used to model trajectories between Origin and Destination (OD).	(3) Flight trajectories are dispersed around the Great Circle using trajectory distributions developed from analyzing radar trajectories.
(4) Unscheduled and cancelled flights were not accounted for.	(4) An airport-based factor has been introduced to empirically account for the effects of unscheduled and cancelled flights.
(5) Goal of the study was to develop a static inventory of fuel burn and emissions.	(5) Goal in developing SAGE was to develop a model that could be used to generate inventories of fuel burn and emissions. This allows SAGE to be used for various other studies using dynamic modeling components (e.g., as opposed to static lookup tables).
(6) Airport delays were not modeled.	(6) Airport delay-modeling capabilities are included in SAGE, thereby providing a dynamic capability to assess capacity/delay issues.

the corresponding improvements that have been incorporated into SAGE. Although the “past study” depictions are not applicable to all of these studies, they still represent the bulk.

This is the first paper in a two-part series that provides the technical background on SAGE, describing the computational components and the input/output databases. The second paper provides an assessment of uncertainties within the model and a sample application for making policy decisions. The output inventory data are provided in this first paper to exemplify the types of information that can be obtained from SAGE. This is followed by comparisons to the results from previous studies, and the initial results from validation assessments are also provided.

2. Model overview

The fundamental modeling unit in SAGE is a single flight. All data including those related to flight schedules, trajectories, performance, and emissions are represented at a level of detail sufficient to support the modeling of a single flight. This allows high-fidelity modeling of global inventories of fuel burn and emissions, where all commercial flights worldwide for each day of the year are simulated. Each flight is modeled from gate-to-gate, as indicated in Fig. 1.

Although a single flight in SAGE is the modeling unit, the simulation is conducted at a more detailed level. That is, the emissions for each individual segment of a flight, referred to as a flight chord, are estimated. Typical flights in SAGE are currently represented by 40–50 chords, depending on the stage length and availability of detailed radar trajectory data. The flight chords allow the freedom to express the outputs in a variety of different formats (e.g., gridded and per flight mode) and allow for dynamic aircraft performance modeling in SAGE, which results in greater degree of options for scenario modeling. Such modeling provides an opportunity for improvements in accuracy relative to those based on aggregated times in mode (TIM) or simplified performance lookup tables.

The current worldwide coverage in SAGE includes approximately 30 million commercial flights per year and accounts for over 200 different aircraft types. Even though substitution aircraft data are necessarily used for some aircraft types, the intention with SAGE is to preserve as much of the specificity for each flight as possible. Therefore, compromises associated with using generic aircraft types and engines as the starting point are not made. The current input databases allow SAGE to be used to model flights for all years from 2000 to 2006.

To accomplish the detailed flight-by-flight modeling, SAGE includes various aircraft fleet, operations, and performance data, as well as the modules to process the information and perform computations. The basic computational modules and outputs are shown in Fig. 2. The following sections provide an overview of the computational modules and the corresponding databases (see also, Federal Aviation Administration, 2005a).

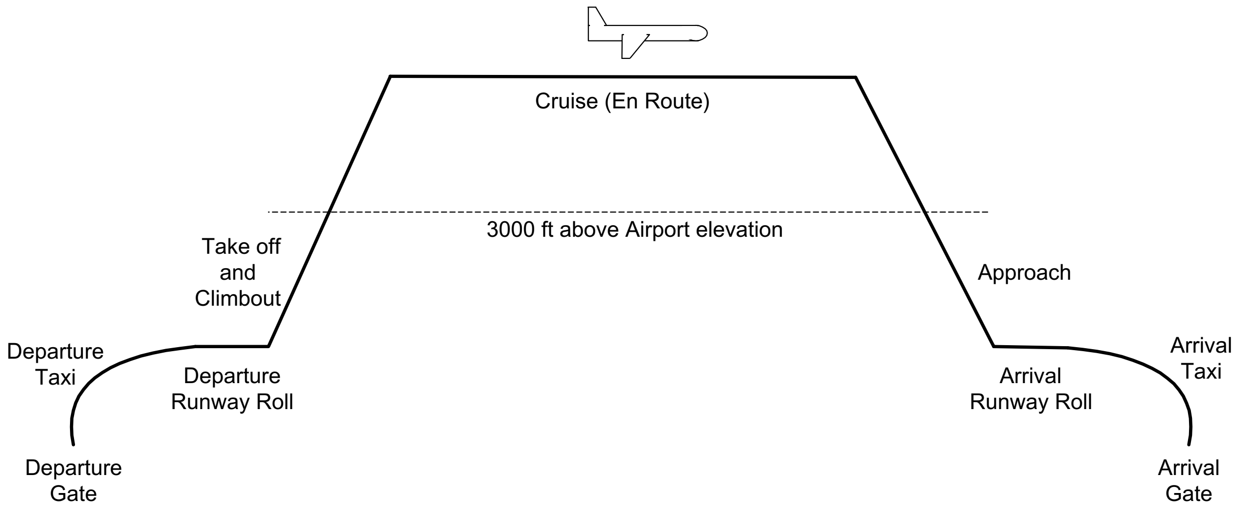

Fig. 1. Full gate-to-gate flight modeling in SAGE.

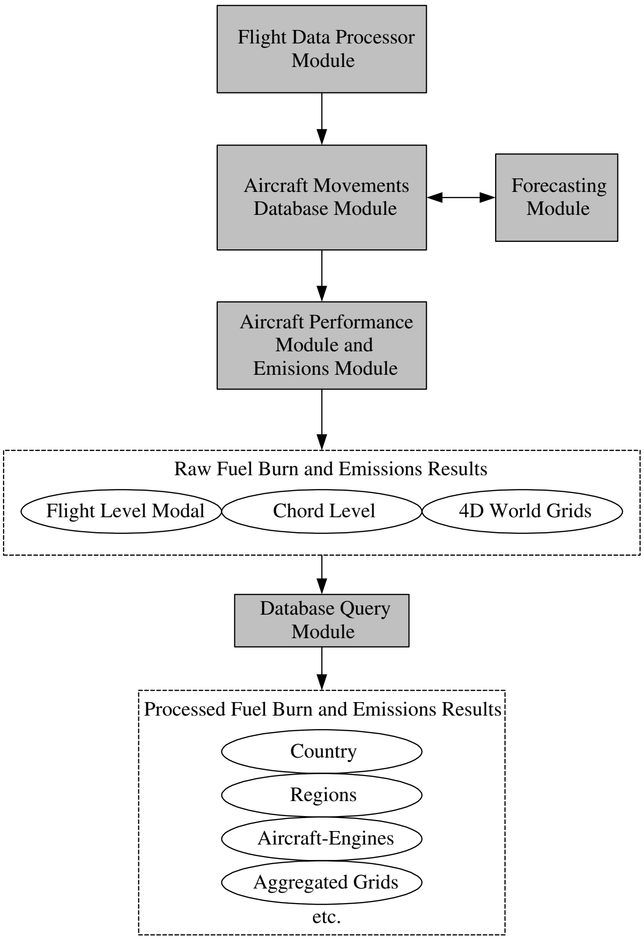

Fig. 2. Overview of the main modules and databases in SAGE.

3. Flight data processor module

The Flight Data Processor Module conducts the initial processing to prepare flight plans/schedules and trajectories. The processing is conducted on two main databases: the Enhanced Traffic Management System (ETMS) and the Official Airline Guide (OAG) (Federal Aviation Administration, 2005a,d; Volpe, 2003). ETMS provides radar data and reported flight plans, while OAG only provides planned schedules of flights by commercial airlines. Therefore, when ETMS and OAG flight data matches, the OAG flight is dropped in favor of the ETMS flight. ETMS coverage currently includes North America and parts of Western Europe. The current ETMS and OAG flight coverage on a global basis is about even (each accounting for roughly half) with some variations from year to year. This ETMS coverage includes flights that have both flight plans and radar trajectories as well as just flight plans. Approximately 45% of ETMS flights (or about 22.5% of all global flights modeled in SAGE) include radar data.

4. Aircraft movements database module

The creation of the aircraft movements database represents an aggregation of ETMS, OAG, and various supporting data. Although this is shown as a separate process in Fig. 2, it is a continuation of the flight data processing. The purpose of both modules is ultimately to create a processed movements database that can be used to estimate fuel burn and emissions.

The aircraft type for each flight in SAGE is identified through the use of aircraft codes specified in the ETMS and OAG flight plans and schedules, respectively. These codes are mapped to the aircraft listings within the SAGE performance databases. In many cases, the mappings are perfect (or nearly so) while in other cases, mappings require substitutions because an exact match to the ETMS/OAG aircraft type may not exist in the performance databases. It is estimated that about 90% of flown-distances modeled in SAGE reflect good to perfect aircraft mappings. In contrast to a perfect map, an example of a good map would be a mapping between an Airbus A341 and an Airbus A343. The remaining 10% are substitutions, such as an Ilyushin IL86 with an Airbus A343. The objective in SAGE is to retain as much specificity as possible in defining the aircraft types (over 200 types are represented) in contrast to using a smaller set of representative aircraft as an approximation of the world fleet.

The ETMS and OAG flight plan and schedule data do not provide engine listings. The engine type is assigned based on one of three methods. The first and preferred method is through an exact assignment by identifying the tail number of the aircraft from the Bureau of Transportation Statistics (BTS) Airline On-Time Performance data through matchings of flight ID numbers and aircraft type. Once this is accomplished, the tail number is matched to the one in BACK Aviation's world fleet database and the exact engine is assigned. The BACK world fleet database contains a listing of worldwide commercial aircraft built since 1940 and provides various aircraft-specific information including tail numbers, engine types, weight, size, seating, and airline (BACK, 2005).

Since the BTS data cover only the top 10 US airlines, many flights cannot be assigned exact engines. The second method is to assign engines based on popularity within the world fleet. The BACK world fleet database is used to develop distributions of engine counts based on airline and aircraft categories as provided in the BACK database. The third method involves the use of default engines for each specific aircraft type. In some cases, the airline codes or a combination of the airline and aircraft codes will not match any from BACK. In that case, the default engines provide the only recourse to assigning engines. These default engines are generally the most popular for each aircraft type (Federal Aviation Administration, 2005b). Most of the engines are assigned based on the distributions from the second method, as shown by the approximate percentages of flights using the different methods:

- First method (BTS and BACK tail number and match): 14%.
- Second method (BACK distribution): 77%.
- Third method (default engine): 9%.

Due to the use of OAG flight schedules for areas outside of ETMS coverage, unscheduled and cancelled flights cannot be directly modeled. Instead, their effects are indirectly accounted for through the use of scaling factors that generally increase the number of flights. The factors are a function of the scheduled OAG flights (operations) at an airport, and were developed based on a comparison analysis of ETMS and OAG flights (Federal Aviation Administration, 2005a). The factors are applied at the flight level and allow for a more accurate accounting of global fuel burn and emissions. With the use of ETMS data, the factors have very little effect in North America since only a few OAG flights are modeled for that region. For other regions such as Western Europe, a comparison of OAG schedules and reported flight plans from the Eurocontrol Experimental Center for the top 20 European airports in October 2003 have shown that unscheduled flights can account for over 9% of flights.

For those flights that do not have trajectories (e.g., OAG flights and ETMS flights with erroneous trajectory data that could not be salvaged), cruise trajectory distributions are used to assign trajectories. The altitude and latitude/longitude distributions were developed by analyzing four months worth (October and May of 2000 and 2003) of ETMS flights. The distributions provide more accurate modeling of flight distances, as opposed to using a single Great Circle path between two points, which has been applied in other inventory and modeling studies such as those by NASA/Boeing (Baughcum et al., 1996a,b; Sutkus et al., 2001; Intergovernmental Panel on Climate Change, 1999). As suggested in the ANCAT/EC2 study, the extra distance flown due to deviation from the Great Circle may account for 10–11% of the total flight distance on average (Gardner, 1998).

As part of the movements, delays are modeled in SAGE through a sub-model called, WWLMINET (Federal Aviation Administration, 2005b; Stouffer, 2002). WWLMINET is a "worldwide" version of LMINET (NASA, 1998), a queuing model that predicts hourly airport ground and approach airborne delays. WWLMINET starts with a flight demand that is propagated through a network of queues. The delays associated with serving that demand level are determined. The WWLMINET network currently contains 102 US airports, 122 European airports, and 33 other airports (i.e., outside of US and Europe). Together these 257 airports represent approximately 75% of global commercial air traffic as defined by the OAG schedules. Airports not included in this network are assumed to have no delays.

5. Aircraft performance module

In SAGE, aircraft performance is modeled dynamically using a combination of the data and methodologies found in the FAA's Integrated Noise Model's (INM) (Federal Aviation Administration, 2002) implementation of the Society of Automotive Engineers (SAE) Aerospace Information Report (AIR) 1845 (SAE, 1986) and Eurocontrol's Base of Aircraft Data (BADA) Version 3.6 (Eurocontrol Experimental Center, 2004). The INM and BADA methods were employed within SAGE in large part because they are publicly available, and thus are in accordance with FAA's intent to keep all SAGE methods and data sources non-proprietary. These models also provide a comprehensive set of aircraft data that allows modeling of the world fleet. BADA provides aircraft performance data for cruise, while INM provides performance for the landing and takeoff (LTO) modes. BADA's speed schedule is used for LTO for consistency, and BADA's fuel flow coefficients are used for all modes, since INM currently does not model fuel flow. Although BADA can be used to model all modes, the INM data and methods were implemented for LTO modeling because INM has been extensively validated and is internationally recognized and accepted (Flathers, 1982).

Atmospheric information pertinent to flight performance, such as temperature and pressure, are based on the International Standard Atmosphere (ISA) where temperature and pressure at sea-level are defined as 288.15 K (59 °F) and 101325 Pa (1 atm), respectively. Relative humidity and the specific heat ratio are assumed to be constant at 60% and 1.4, respectively. It is expected that future versions of SAGE will incorporate meteorological data from assimilated weather models (e.g., globally gridded data) in place of the ISA assumption.

6. Emissions module

SAGE generates estimates of the emissions of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), carbon dioxide (CO_2), water (H_2O), and sulfur oxides (SO_x modeled as SO_2) for each flight chord. CO, HC, and NO_x emissions are modeled using Boeing Fuel Flow Method 2 (BFFM2) (Baughcum et al., 1996a; DuBois and Paynter, 2006). CO_2, H_2O, and SO_x emissions are modeled based on fuel composition using Boeing-derived emissions indices (EI) (Hadaller and Momenthy, 1989, 1993). These methods and data have been used in various inventory projects, examples of which can be found in Baughcum et al. (1996a,b, 1998a,b), Daggett et al. (1999), Sutkus et al. (2001) and Intergovernmental Panel on Climate Change (1999). A review of BFFM2 by the Alternative Emissions Methodology Task Group (AEMTG) of ICAO CAEP Working Group 3 (WG3) resulted in the conclusion that the method is an acceptable approach for modeling emissions with uncertainties in the ±10% range for NO_x and CO, and up to ±15% for HC (International Civil Aviation Organization, 2004). Partly because of this type of recognition and also because it is publicly available, BFFM2 has seen increased international use in recent years.

BFFM2 uses jet engine emissions indices and corresponding fuel flows from the ICAO engine certification databank to model CO, HC, and NO_x emissions (International Civil Aviation Organization, 1995; QinetiQ, 2004). For turboprops, similar data from the FAA Emissions and Dispersion Modeling System (EDMS) (Federal Aviation Administration, 2004) are used with BFFM2. The key components within BFFM2 are adjustments for altitude (e.g., atmospheric effects) and the development of a relationship between EI and fuel flow. The latter component allows a predicted fuel flow from BADA to be used to predict emissions.

7. Forecasting module

The forecasting module within SAGE requires, among other information, flight forecasts from the FAA's Terminal Area Forecast (TAF) (US Department of Transportation, 1999; Federal Aviation Administration, 2005e) and ICAO's Forecasting and Economics Sub Group (2003) projections. The method involves growing a week's worth of OAG scheduled flights to represent the growth in demand for a future year. A week was found to be a good compromise between accuracy and computational efficiency as explained in Federal Aviation Administration (2005a).

The TAF projections are airport-based whereas FESG projections are based on large-scale regional and route categories. Within SAGE, TAF information takes precedence over the FESG data when modeling US flights covered under the TAF. Growth for the remaining flights in the rest of the world is based on FESG forecasts. Also included in the forecasting methodology is an aircraft retirements and replacements algorithm that uses retirement parameters from FESG. The result is a future schedule of flights that reflects the effects of fleet growth and retirements with replacements.

8. Raw inventory descriptions

The basic outputs from SAGE are fuel burn and emissions of CO, HC, NO_x, CO_2, H_2O, and SO_x (modeled as SO_2). These data and others are generated by SAGE as part of three raw inventories: flight-level, chord-level, and 4D world grids. The flight-level inventory contains individual listings of each of the 30 million per year civil flights worldwide. The chord-level inventory contains a listing of individual flight chords for all flights worldwide, resulting in over a billion yearly records. The 4D world grid inventory contains a listing of individual flight segments similar to the chord-level inventory, but the more than a billion segments correspond to the portions of the chords that traversed a grid. These inventories are generated for each year and stored in a relational database (Federal Aviation Administration, 2005b).

9. Processed inventories

Since the raw inventories have been stored in a relational database, they can be easily queried to generate various derivative inventories. These processed inventories are the results of further categorizations, aggregations, and computations using the raw data (Federal Aviation Administration, 2005b).

Overall, the global fuel burn and emissions totals are presented in Table 2. These results and all that follow do not include piston-powered aircraft, as they have been excluded due to the uncertainties associated with emissions data for piston-power aircraft. Piston-powered flights account for approximately 2% of propeller (piston plus turboprops) and approximately 0.05% of total (propeller plus jet) fuel burn.

In general, as more fuel is burned, more emissions are likely to be generated. As expected, emissions of CO_2, H_2O, and SO_x follow the same yearly trend as fuel burn since they are modeled strictly based on fuel composition assuming 100% combustion of the fuel. NO_x emissions also follow fuel burn trends but less than the aforementioned pollutants due to some non-linear effects. CO and HC follow fuel burn trends the least due to stronger non-linear effects. These non-linear effects are due to the behavior of the combustion process as a function of throttle setting and are reflected in the emissions indices used from the ICAO Emissions Databank.

Average global fuel efficiency metrics (i.e., fuel burn per distance) and average EI values derived from global totals (e.g., total grams of NO_x per total kilogram of fuel burn for EI NO_x) are presented in Table 3. The fuel efficiency metric indicates that there may be a 1–2% annual global increase in efficiency over the six years presented. This trend is consistent with the findings in Lee et al., 2001 that show historical decreases in cruise

Table 2
Yearly global total fuel burn and emissions

Year	Flights (millions)	Distance (nm)	Fuel burn (Tg)	NO_x (Tg)	CO (Tg)	HC (Tg)	CO_2 (Tg)	H_2O (Tg)	SO_x (Tg)
2000	29.7	1.80E+10	181	2.51	0.541	0.0757	572	224	0.145
2001	27.7	1.72E+10	170	2.35	0.464	0.0630	536	210	0.136
2002	28.5	1.76E+10	171	2.41	0.480	0.0639	539	211	0.137
2003	28.8	1.86E+10	176	2.49	0.486	0.0617	557	218	0.141
2004	30.4	2.00E+10	188	2.69	0.511	0.0625	594	233	0.151
2005	32.4	2.20E+10	203	2.90	0.554	0.0652	641	251	0.163

Table 3
Yearly global derived metrics of fuel efficiency and emissions indices

Year	Fuel burn per distance (Tg/Billion km)	EI NO_x (g/kg)	EI CO (g/kg)	EI HC (g/kg)	EI CO_2 (g/kg)	EI H_2O (g/kg)	EI SO_x (g/kg)
2000	5.43	13.8	2.98	0.417	3155	1237	0.8
2001	5.33	13.8	2.73	0.371	3155	1237	0.8
2002	5.23	14.1	2.81	0.374	3155	1237	0.8
2003	5.12	14.1	2.76	0.350	3155	1237	0.8
2004	5.08	14.3	2.71	0.332	3155	1237	0.8
2005	4.99	14.2	2.72	0.320	3155	1237	0.8

Table 4
LTO and cruise fuel burn and NO_x emissions (is this modal split consistent with the latest from the AEDT NO_x prototype?)

Year	Fuel burn (Tg)		NO_x (Tg)	
	LTO	Cruise	LTO	Cruise
2000	12.9	168	0.197	2.31
2001	12.3	158	0.191	2.16
2002	12.2	159	0.194	2.22
2003	12.4	164	0.199	2.29
2004	12.9	175	0.210	2.48
2005	13.9	189	0.227	2.67

specific fuel consumption (sfc), energy intensity defined as energy (or fuel) used per revenue passenger kilometer, and energy used per available seat kilometer.

The global modal splits of fuel burn and NO_x emissions are presented in Table 4. Three thousand feet above field elevation (AFE) is used to differentiate between the LTO cycle and cruise. Field elevation refers to an airport's altitude above sea level. Since NO_x tends to follow fuel burn trends well, the cruise to LTO ratios are similar for both fuel burn (13.2 average) and NO_x (11.6 average). These ratios are approximately constant for each of the six years.

The global fuel burn and emissions separated into jet and turboprop categories are shown in Table 5. As expected, the jet contribution to global fuel burn and NO_x emissions is greater than the contribution of turboprops due to the greater number of jet operations and higher fuel consumption on a per flight basis. Similar to the cruise and LTO comparisons, the jet to turboprop ratio is also similar when comparing fuel burn and NO_x. However, the ratios appear to be different from year to year. The ratios increase from about 42–43 to about 60–62 from 2000 to 2005, possibly indicating an increase in jet usage or a decrease in turboprop usage.

Yearly regional totals for fuel burn and NO_x are shown in Figs. 3–6. The attribution of fuel burn and emissions to each of the regions is based on the location or ownership of the departure airport. Fig. 7 shows a plot illustrating the worldwide locations of airports color-coded by region. All fuel burn and emissions for a flight are attributed to a region containing the airport and are either categorized as domestic or international

Table 5
Global fuel burn and NO_x emissions separated into jet and turboprop categories

	Fuel burn (Tg)		NO_x (Tg)	
Year	Jet	Turboprop	Jet	Turboprop
2000	177	4.25	2.45	0.0569
2001	166	3.48	2.30	0.0486
2002	167	3.51	2.37	0.0485
2003	173	3.28	2.45	0.0470
2004	185	3.28	2.64	0.0468
2005	200	3.31	2.85	0.0463

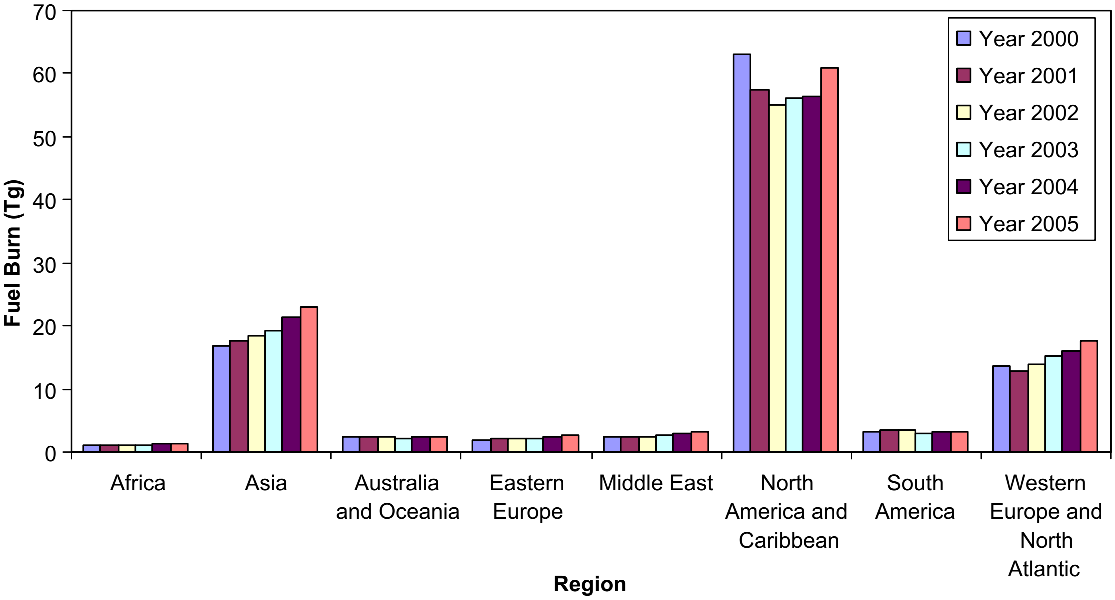

Fig. 3. Comparison of regional domestic fuel burn.

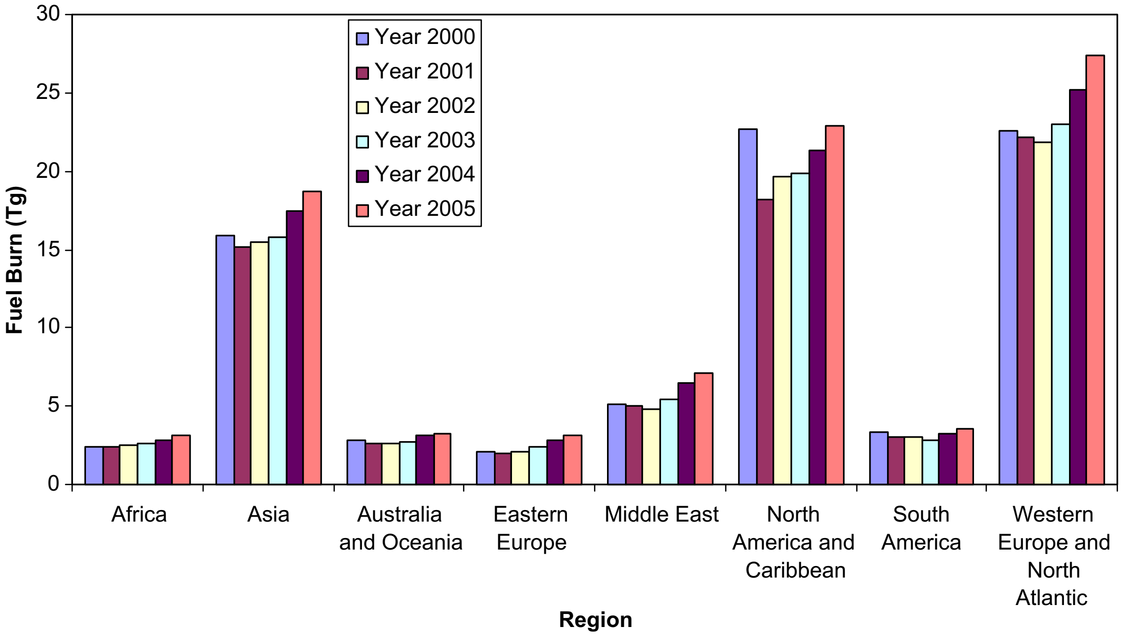

Fig. 4. Comparison of regional international fuel burn.

depending on whether or not the arrival airport is within the same country/region. The following examples illustrate this scheme:

- Flight 1: Region A, Domestic
  - Departure airport in Region A
  - Arrival airport in Region A

- Flight 2: Region A, International
  - Departure airport in Region A
  - Arrival airport in Region B

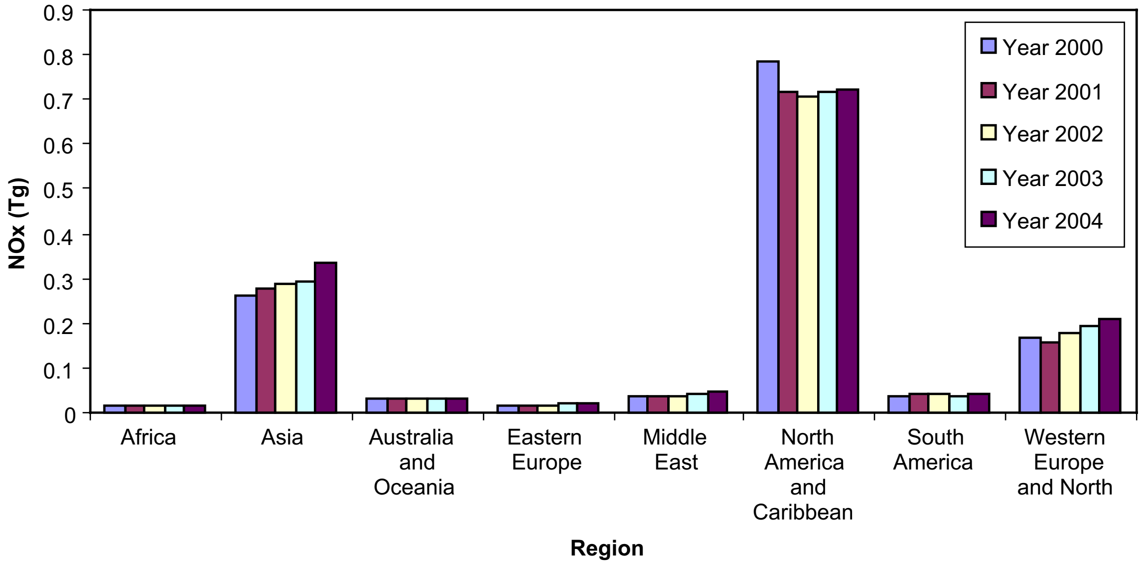

Fig. 5. Comparison of regional domestic NO_x emissions.

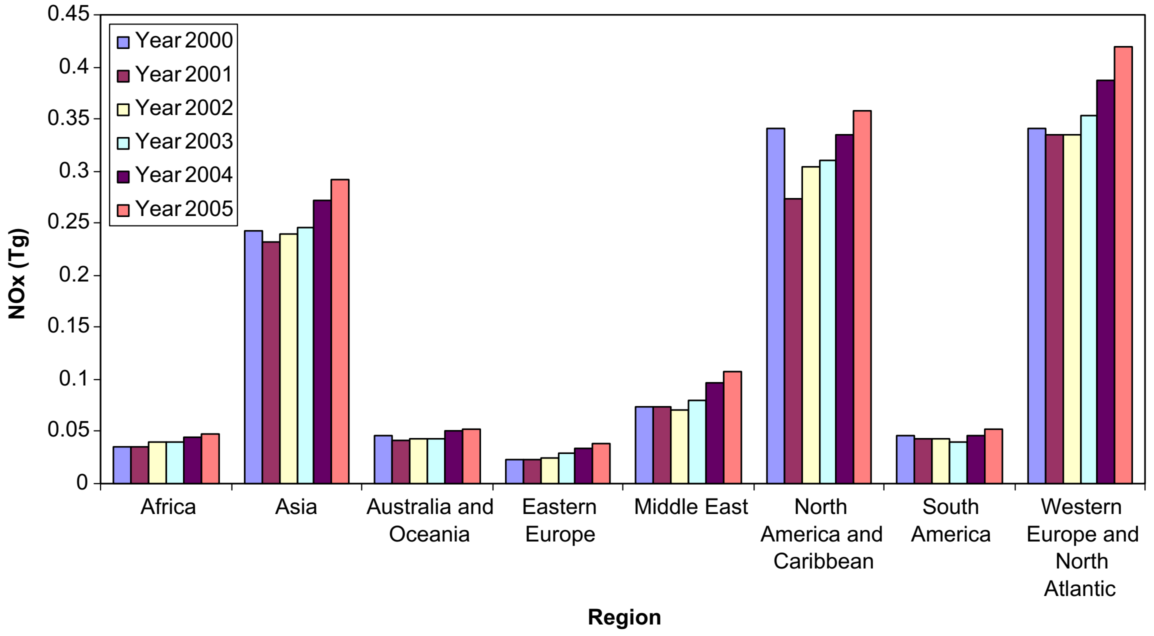

Fig. 6. Comparison of regional international NO_x emissions.

The fuel burn and emissions resulting from Flight 1 are attributed to the Region A, domestic category because both the departure and arrival airports are in Region A. In contrast, the fuel burn and emissions for Flight 2 are categorized into the Region A, international category because the arrival airport is not within Region A. That is, any arrival Region other than A would result in the same international classification. In accordance with the terminology often used by the United Nations Framework Convention on Climate Change (UNFCCC), the international category can similarly be referred to as a "bunker" category (Intergovernmental Panel on Climate Change, 1997).

The comparisons in Figs. 3 and 4 show that global domestic fuel burn is dominated by the North America and Caribbean region. In contrast, international fuel burn is similar among three regions: Asia, North America and Caribbean, and Western Europe and North Atlantic. The yearly trends in each of these regions

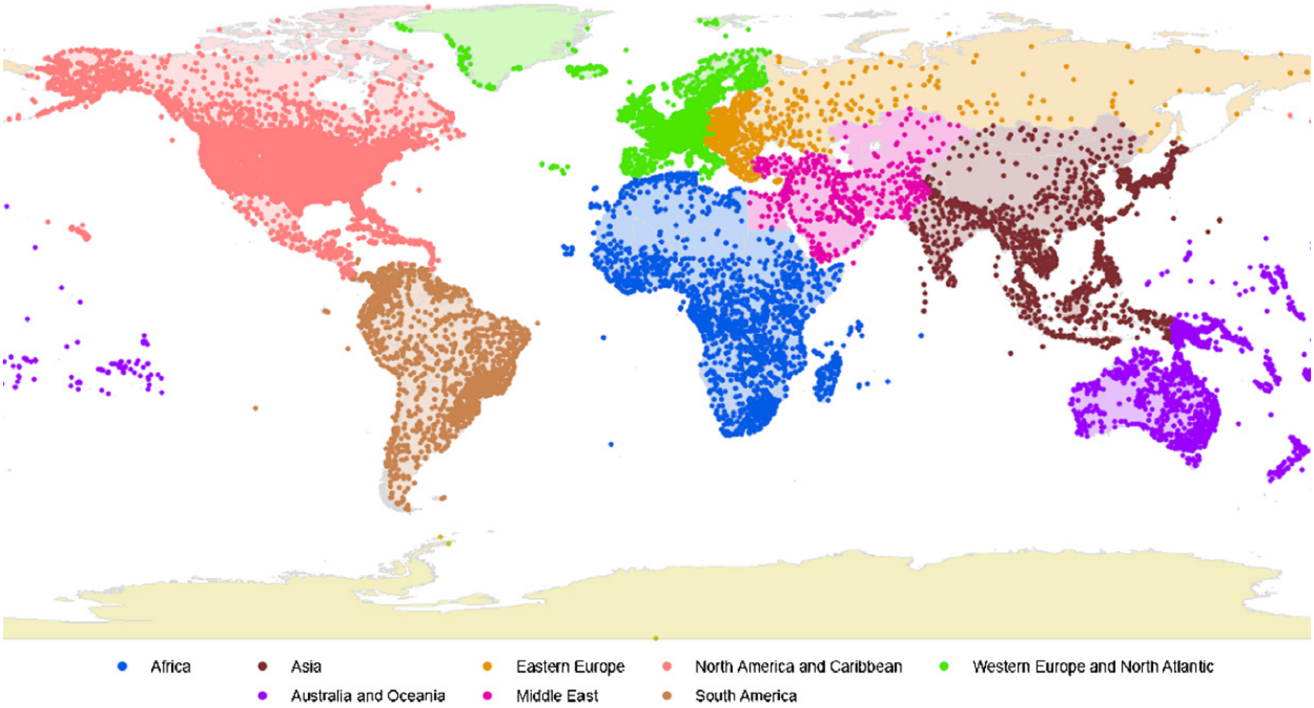

Fig. 7. Worldwide airport locations color-coded by region.

generally show an increase from 2002 to 2005, reflecting the growth in the aviation industry. However, decreases shown from 2000 to the following years reflect the effects of the events of September 11, 2001. As

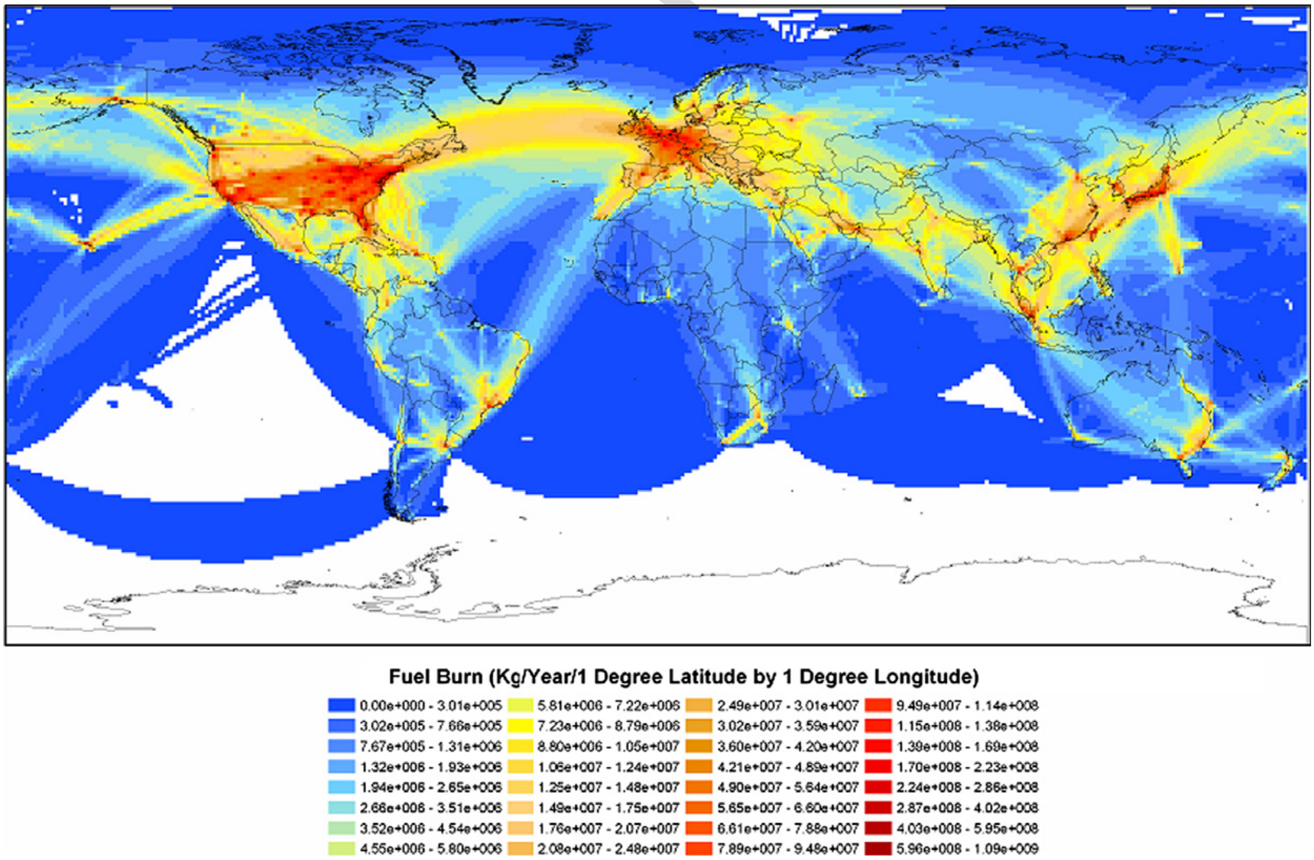

Fig. 8. Gridded plot of global fuel burn for 2000 with all altitudes aggregated.

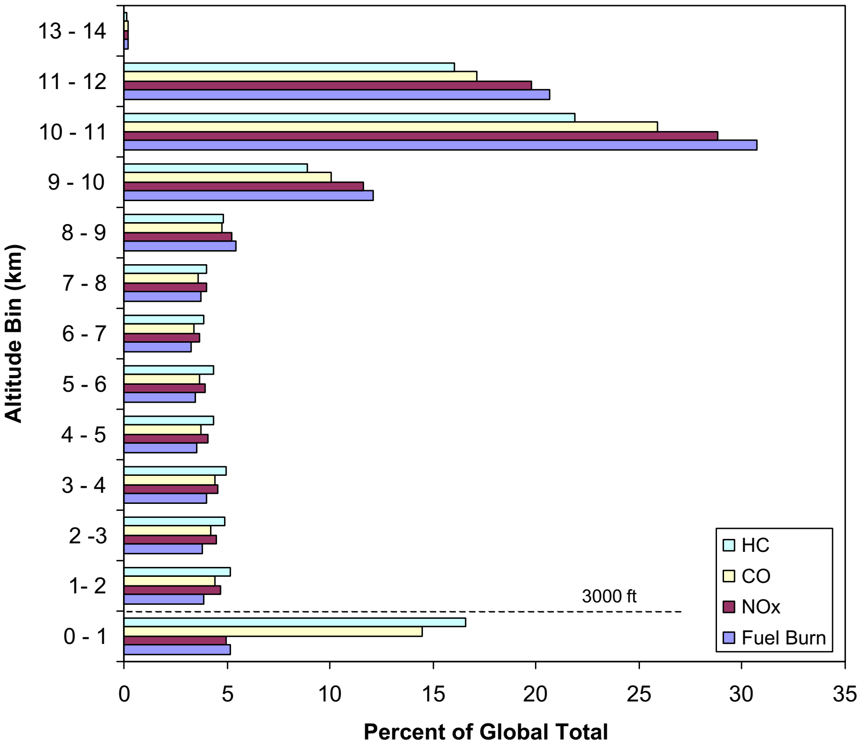

Fig. 9. Altitude distribution of fuel burn and emissions for year 2000.

expected, the NO_x comparisons shown in Figs. 5 and 6 follow the same distributions shown by the fuel burn comparisons. Although these aggregations of fuel burn and emissions were generated at a regional level, they can be conducted for smaller areas including countries, states, and cities, as long as the airports have been appropriately categorized into those areas.

Examples of processed, gridded fuel burn and emissions inventories are shown in Figs. 8 and 9. Fig. 8 shows where most of the fuel is burned: North America, Western Europe, and Eastern Asia. Fig. 9 shows a distribution of total fuel burn and emissions by 1 km altitude bins for year 2000. The altitude bins with the highest fuel burn and emissions are between 9 and 12 km (or approximately 29,500 ft and 39,400 ft). This corresponds to the frequent use of these altitudes for the cruise flight segment. The relatively high levels of HC and CO in the 0 to 1 km band (i.e., below 3000 ft AFE) are due to the higher emission rates per unit fuel burn for those pollutants at lower aircraft power settings (e.g., during taxiing, idle, and approach conditions).

10. Comparisons with past studies

A comparison of SAGE results to those from various past studies was conducted to assess the results from SAGE. Figs. 10–13 show comparisons of SAGE global fuel burn and emissions with those from the following past studies (Intergovernmental Panel on Climate Change, 1999):

- NASA/Boeing inventories for 1976, 1984, 1992 and 1999 (BACK, 2005, 1996a; Sutkus et al., 2001).
- ANCAT/EC2 inventories for 1991/92 (Gardner, 1998).
- DLR inventories for 1992 (Schmitt and Brunner, 1997).
- AERO-MS inventories for 1992 (Pulles, 2002).

The plots in Figs. 10 and 11 (fuel burn and NO_x) show agreement with the general trends established from the past studies, but some differences are apparent. Of all the past studies shown, the closest comparison with SAGE results should be with the NASA/Boeing Scheduled inventories, since SAGE currently only accounts for commercial traffic. The other past inventories labeled as Civil and Global include general aviation and

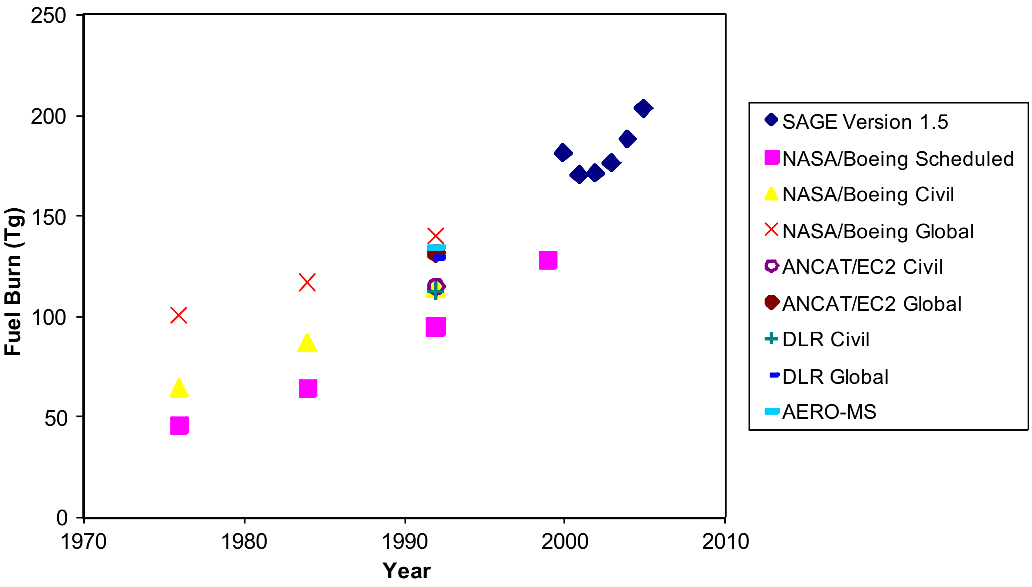

Fig. 10. Comparison of SAGE global fuel burn with past studies.

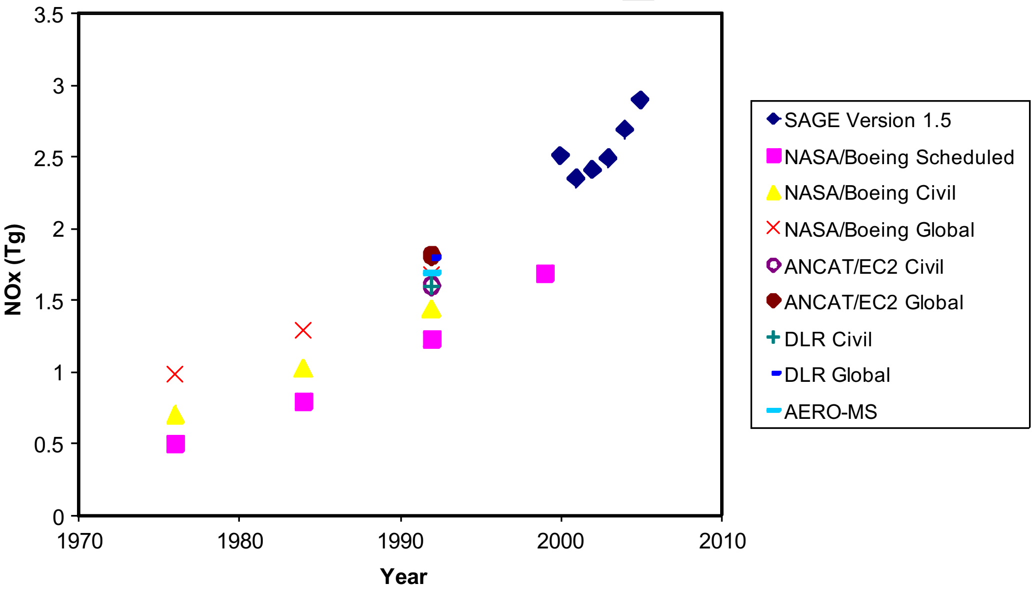

Fig. 11. Comparison of SAGE global NO_x emissions with past studies.

military flights, respectively, and would therefore not be ideal to compare against the SAGE results. Notwithstanding some natural growth in the aviation industry, the approximately 30% difference between the 1999 NASA/Boeing Scheduled inventory totals and the 2000 SAGE totals may in part be explained through differences in trajectory modeling (e.g., Great Circle used by NASA/Boeing versus track distributions used in SAGE) and the inclusion of the effects of unscheduled flights in SAGE (unaccounted in the NASA/Boeing studies). If general aviation and military flights are included in a future version of SAGE, a more appropriate comparison of global totals can be conducted. A study estimated that military aviation in the US is responsible for approximately 15% additional fuel burn (Waitz et al., 2005).

The CO and HC comparisons in Figs. 12 and 13 indicate that SAGE results are noticeably different from those suggested by the trends from the past studies. Notwithstanding the differences in distance modeling and unscheduled flights coverage, these types of disagreements with CO and HC are not unexpected since the two

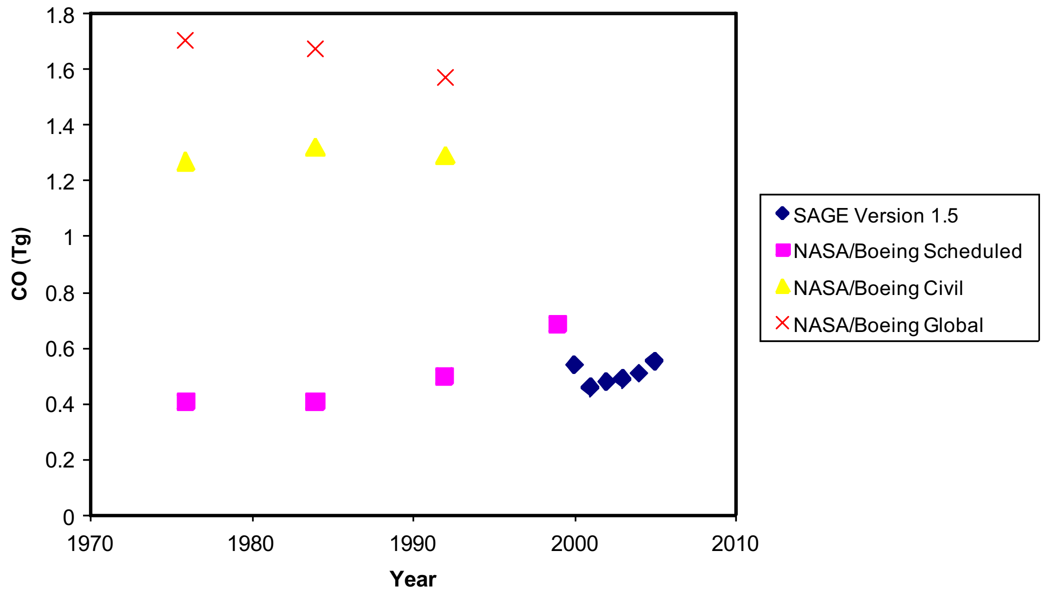

Fig. 12. Comparison of SAGE global CO emissions with past studies.

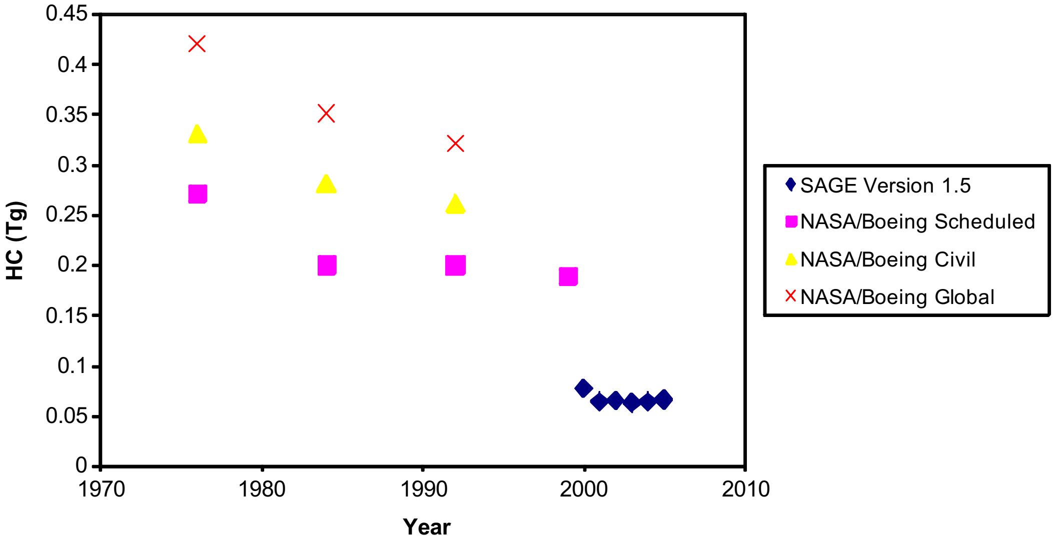

Fig. 13. Comparison of SAGE global HC emissions with past studies.

pollutants have a greater degree of variability with fuel flow than other pollutants like NO_x. Unlike NO_x, small changes in fuel flow could result in much larger changes in CO and HC due to the nature of the modeled relationship between fuel flow and EI values. Also, the use of simplified TIM values for LTO, including taxi and idle activities, in the previous studies could have significantly contributed to these differences.

To investigate all of these differences further, the overall global emissions indices (i.e., total grams of pollutant divided by total kg of fuel burn) for each of the pollutants were compared as shown in Figs. 14–16. The NO_x EI comparisons in Fig. 14 show relatively good agreement with trends suggested by past studies. The difference between the 1999 NASA/Boeing Scheduled EI value and the 2000 SAGE value is about 5%. In contrast, the differences for CO and HC EI values are much greater, as shown in Figs. 15 and 16. These results indicate that the differences in NO_x totals (Fig. 14) are less likely due to differences in EI modeling than the aforementioned differences in flight coverage, distance modeling, etc.

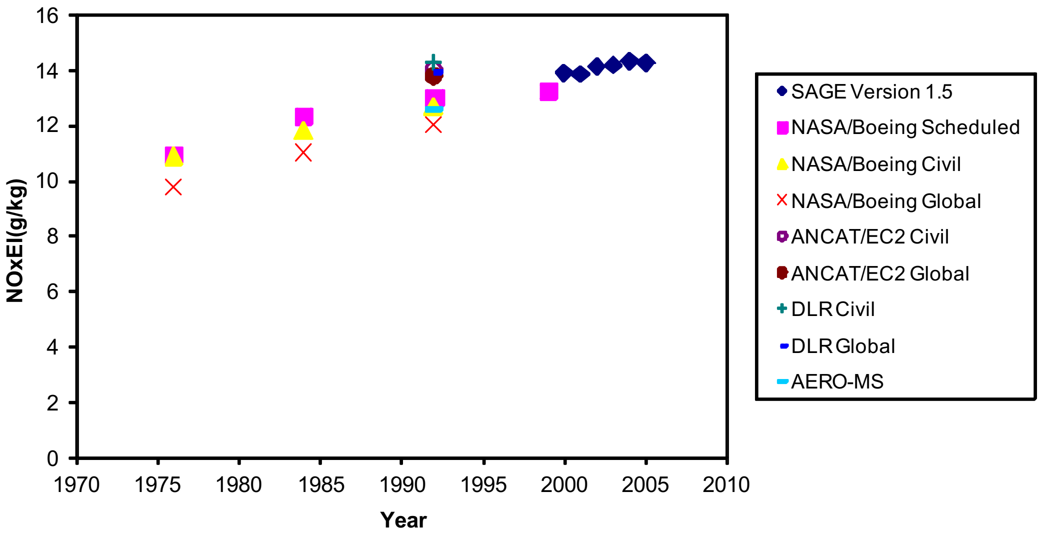

Fig. 14. Comparison of SAGE global average NO_x EI values with past studies.

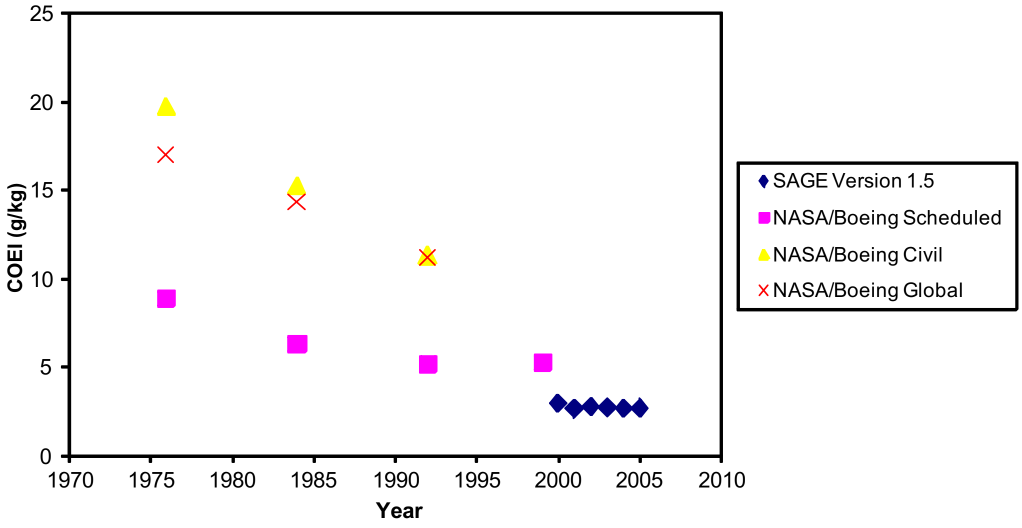

Fig. 15. Comparison of SAGE global average CO EI values with past studies.

An aircraft-level cruise NO_x EI comparison of a dozen selected aircraft types is shown in Fig. 17. These aircraft are some of the most widely flown in the current world fleet. The NO_x EI comparisons show reasonable agreement between the two datasets. Although a couple of aircraft types show noticeable differences such as the Fokker 28 (about 33%) and MD-80 (about 24%), most are within 15% difference. The differences in the NO_x EIs can be attributed to several factors, including differences in the aircraft performance models (i.e., EI is dependent on fuel flow), differences in aircraft and engine mappings, operational changes of the world fleet from 1999 to 2000, and differences in engine assignments. The overall average NO_x EI values for the selected aircraft types are 13.2 g/kg for NASA/Boeing and 13.3 g/kg for SAGE Version 1.5. Similar to the comparisons in Fig. 14, these values indicate that for the global fleet, the performance module in SAGE appears to produce comparable results to those from the past studies.

The large differences in CO and HC EI values as shown in Figs. 15 and 16 appear to support the earlier assertion that the sensitivity of CO and HC EI values to fuel flow could have played a major role in the differences between CO and HC totals shown in Figs. 12 and 13. Fig. 18 shows an example bilinear plot of CO EI versus fuel flow used in BFFM2 for the popular CFM56-3-B1 engine. As indicated in Fig. 18, a small change in fuel flow at the lower power settings (e.g., below 30%) could result in a larger change in CO EI. For

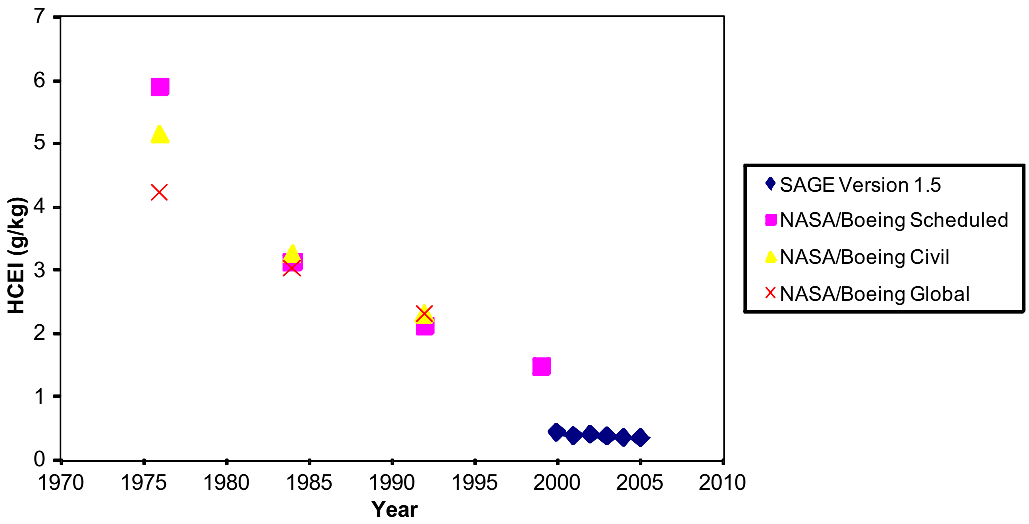

Fig. 16. Comparison of SAGE global average HC EI values with past studies.

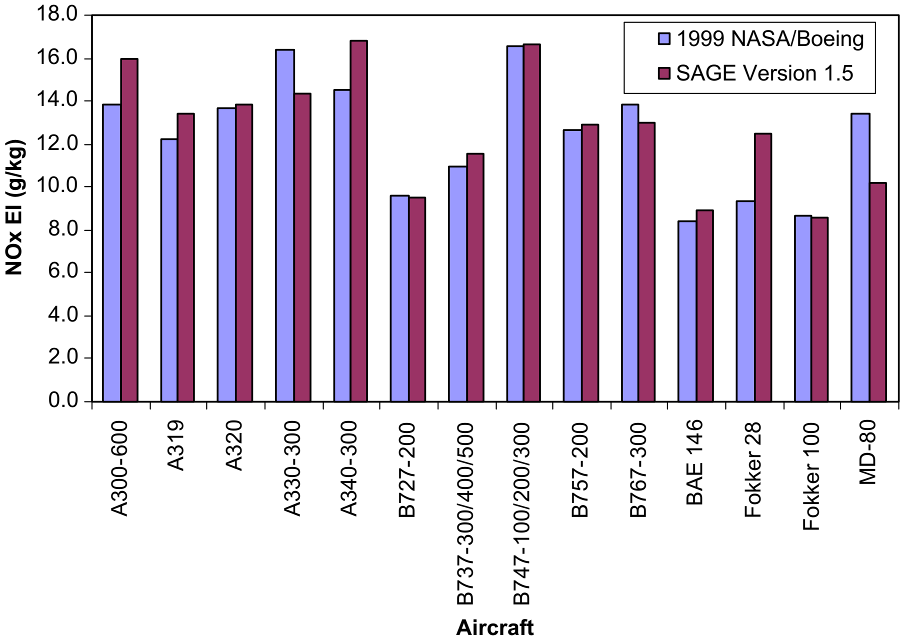

Fig. 17. Comparison of cruise (>1 km altitude above AFE) NO_x EI values for selected aircraft types from SAGE 2000 and NASA/Boeing 1999 inventories.

example, a 10% increase in fuel flow results in about 20% decrease in CO EI at the lower power settings for this example. Since power settings are generally low during cruise, differences in fuel flow modeled between SAGE and the previous studies could have resulted in larger differences in CO and HC.

Another possible cause for the differences may be different engine assignments. Differences in the engine(s) assigned to each aircraft type and the differences in usage (i.e., flight distributions) can cause significant differences in emissions indices and emissions. For example, Table 6 shows some sample CO EI and fuel flow data from the ICAO emissions databank that help illustrate the effect of the differences caused by different engine assignments and usage. The engines in Table 6 are commonly used types on the Boeing 727 and 737 families of aircraft. Even though the fuel flows are relatively similar within each mode, the CO EI values are shown to vary significantly. This is true even within the same engine type due to the use of different

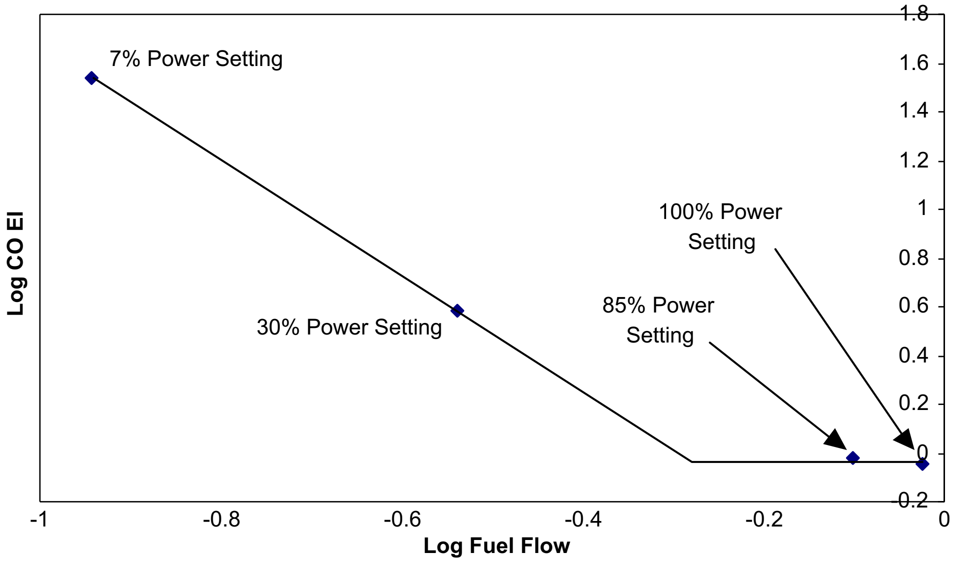

Fig. 18. Example bilinear log–log plot of CO EI versus fuel flow for the CFM56-3-B1 engine.

Table 6
Sample CO EI and fuel flow data from the ICAO engine certification emissions databank

ICAO UID	Engine	Combustor	CO EI (g/kg)				Fuel Flow (kg/s)			
			Takeoff	Climbout	Approach	Idle	Takeoff	Climbout	Approach	Idle
1PW010	JT8D-15	Reduced emissions	1.03	1.15	2.77	11.0	1.178	0.9450	0.3402	0.1477
1PW009	JT8D-15	Smoke fix	0.7	1.0	9.6	35.2	1.178	0.9450	0.3403	0.1477
1PW011	JT8D-15A		1.08	1.2	2.9	12.93	1.115	0.8955	0.3120	0.1372
1PW007	JT8D-9 series	Reduced emissions	1.04	1.11	2.14	14.14	1.040	0.8453	0.2977	0.1323
1PW006	JT8D-9 series	Smoke fix	1.24	1.66	9.43	34.5	1.040	0.846	0.298	0.132

combustors. As a result, even though the aircraft performance is modeled similarly between two different flights, emissions can be significantly different.

11. Model assessment overview

Several module-level and system-level assessments of SAGE have been conducted (Federal Aviation Administration, 2005c). This paper presents results from some of those assessments in order to provide an overview of the accuracy of the model. The modular assessments were conducted by comparing modeled versus measured fuel flow values in order to assess the accuracy of the performance module. The system-level assessments were conducted by comparing aggregate flight-level fuel burn to measured values.

Both of these sets of assessments are relatively higher-level than the detailed component uncertainty assessments conducted in the second SAGE paper (Lee et al., in press). This second paper provides estimates of the component uncertainties and assesses the contributions to the overall errors. In addition, the paper illustrates an application to policy by showing how component uncertainties can be propagated through SAGE to statistically determine how uncertainties in SAGE components contribute to uncertainty in assessing the differences between two policy scenarios.

12. Aircraft performance module assessment

Ten high-resolution flight datasets from a major US carrier (two flights for each of five aircraft types) were used for comparisons covering all modes of flight and movement. Since trajectories, atmospheric data, takeoff weights, and other information from the US carrier's data were directly used in SAGE, these comparisons

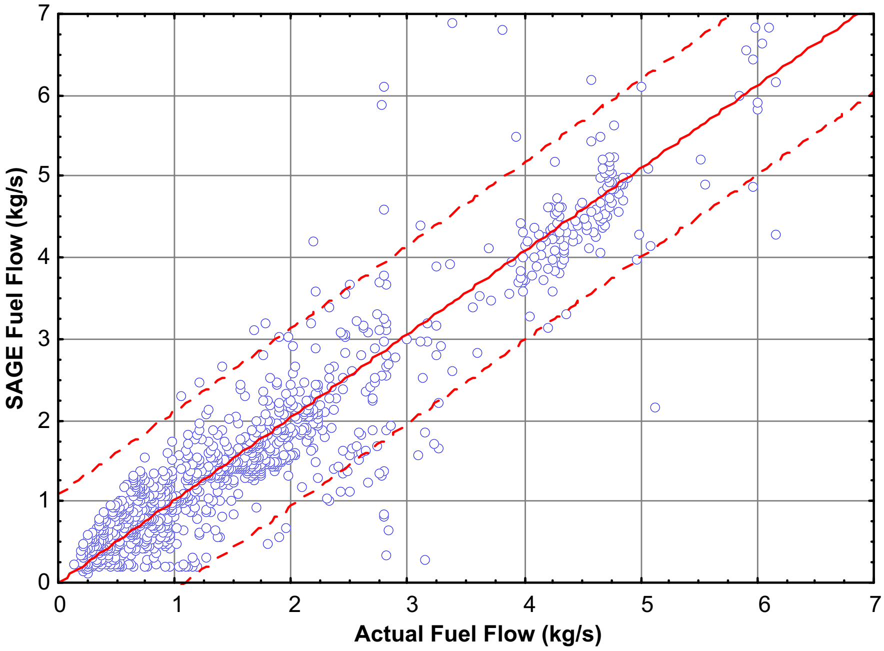

Fig. 19. SAGE fuel flow comparisons against data from a major US carrier.

only assess the overall results of the aerodynamic and engine components of SAGE. Specifically, fuel flows for each of the points along the flight paths were compared. Fig. 19 shows that SAGE accurately predicts the fuel flow for the ten flights with relevant statistics presented below:

- Mean error = 6.95%.
- Standard deviation of errors = 36.7%.
- Sample points = 1449.

In addition to the comparisons against the major US carrier, data from NASA's B757-200 test aircraft were also used. Fig. 20 shows the comparisons against two NASA B757-200 flights, with the resulting statistics presented below:

- Mean error = − 0.24%.
- Standard deviation of errors = 37.3%.
- Sample points = 3537.

Both sets of comparisons show good agreement on an overall basis. And there is no systematic over- or under-prediction.

13. System-level assessment

"System" refers to the fundamental modeling unit of a single flight. Therefore, the system assessment involves comparisons of fuel burn on a flight-by-flight basis. SAGE fuel burn results were generated for nearly 60,000 flights for October 2000. These flights were matched to a major US airline's flights. Unlike the module performance assessment, this system-level comparison takes into account various other items including flight trajectories, aircraft mappings, takeoff weights, etc. The fuel burns for each of these flights were compared as shown in Fig. 21 with the following relevant statistics:

- Mean error = − 2.62%.
- Standard deviation of errors = 13.7%.

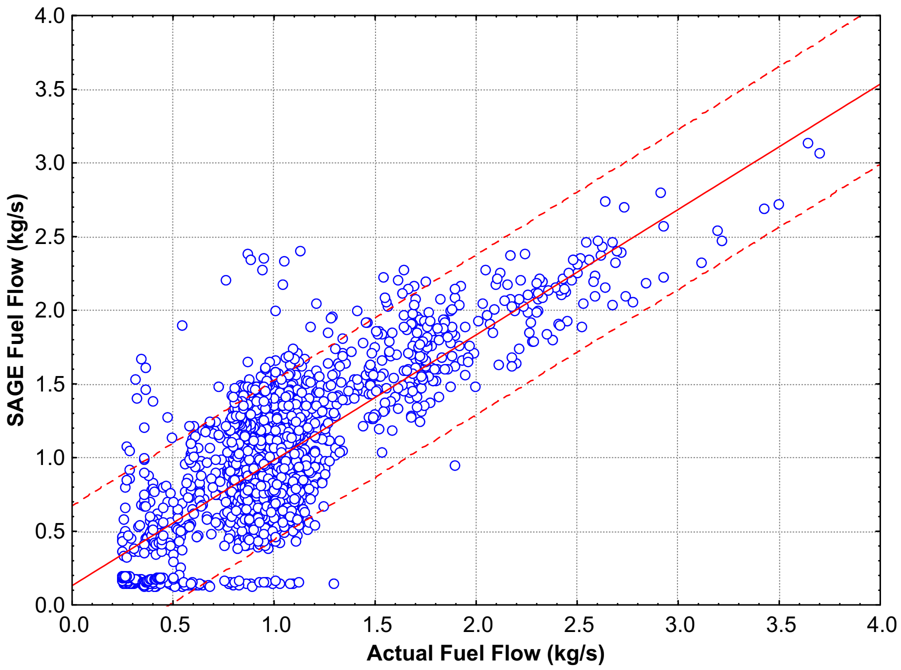

Fig. 20. SAGE fuel flow comparisons against data from NASA.

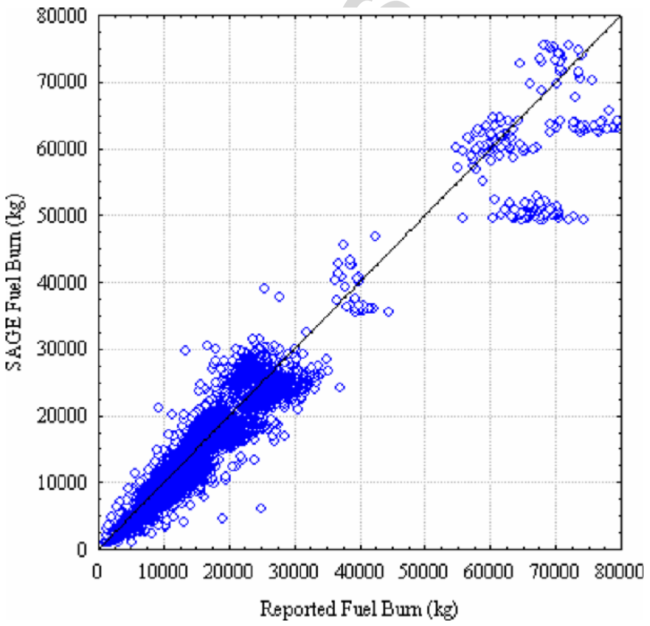

Fig. 21. system-level fuel burn comparisons between SAGE and a major US airline.

- Standard error = 0.06%.
- Median = – 3.79%.
- 95% Confidence interval = 0.11%.
- Number of flights compared = 59,627.

All of the error statistics were generated by first computing the percent differences in fuel burn for each individual flight. The mean error of −2.62% shows good agreement on an overall basis.

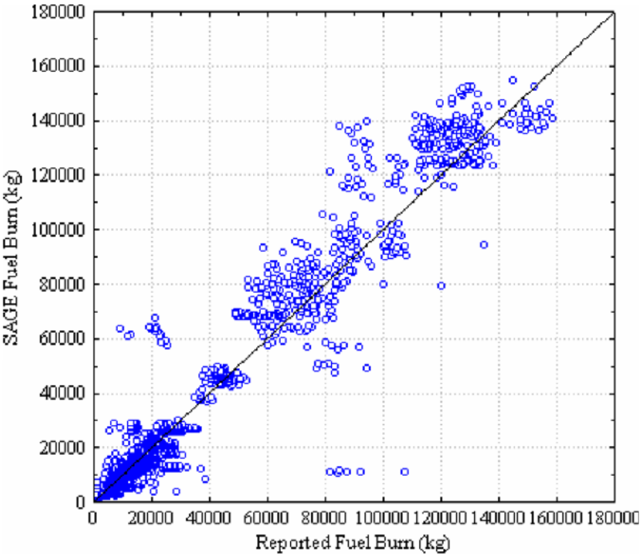

Fig. 22. system-level fuel burn comparisons between SAGE and two major Japanese airlines.

In addition to the comparisons with the major US airline data, the same analysis was conducted for data obtained from two major Asian carriers. In all, nearly 20,000 flights with flight-level fuel burn data from the Japanese airlines were compared against SAGE modeled fuel burn for matching flights. Fig. 22 shows the comparisons with relevant statistics as follows:

- Mean error = 0.42%.
- Standard deviation of errors = 21.5%.
- Standard error = 0.15%.
- Median = – 1.91%.
- 95% confidence interval = 0.30%.
- Number of flights compared = 19,888.

Similar to the comparison with the major US airline data, the mean error of 0.42% shows good agreement on an overall basis in comparing SAGE modeled fuel burn with measured values from two major Japanese airlines. However, the standard deviation of errors of 21.5% is noticeably larger than the corresponding value of 13.7% from the comparisons against the major US airline. This greater scatter of points may be indicative of the fact that none of the Japanese airlines' flights had matching ETMS flights; they were all matched to OAG-based flights that used simulated trajectories. In any case, it is expected that the standard deviation of errors will decrease as the model is improved over time. Some outliers may be due to airline reporting errors and will need to be investigated further during future SAGE validation efforts.

14. Conclusion

SAGE was developed by FAA to provide a modeling capability to estimate aircraft fuel burn and emissions on a global scale based upon non-proprietary databases and methodologies. As such, FAA developed SAGE, now at Version 1.5, from the best publicly available data and methods in order to provide the international aviation community with a high-fidelity tool that can be used to analyze various policy, technology, and operational scenarios for their influence on aircraft fuel burn and emissions.

The model was used to estimate trends of fuel burn and emissions. From 2000 to 2005, the results suggest that global fuel burn increased from 181 Tg to 203 Tg and NO_x increased from 2.51 Tg to 2.90 Tg. However, these increases also reflect recovery from the effects of September 11, 2001 since the totals for each of the years from 2001 to 2002 are lower than those for 2000. Derivative metrics such as fuel burn per distance were also shown to have changed from 5.43 Tg/Billion km in 2000 to 4.99 Tg/Billion km in 2005. This decrease is indicative of more efficient operations of the world's fleet as well as the use of more efficient aircraft types.

The comparison against previous studies showed noticeable differences in the overall, magnitudes of global fuel burn and emissions, but similar trends. The SAGE fuel burn and NO_x results are approximately 30% greater than those expected from the trends exhibited from the previous studies. Since the comparison of NO_x EI values on both global and aircraft levels showed good agreement, the performance model in SAGE appears to be of comparable quality to those used in past studies.

Initial validation assessments have shown that SAGE produces accurate fuel burn results for averages of thousands of flights. However, estimates for any given flight may be off by ±50% or more . An assessment of the aircraft performance module showed that when comparing point-by-point fuel flows from SAGE against data from a major US airline and NASA, the overall agreement was good with mean errors of 6.95% and −0.24%, respectively. Similarly, system-level (aggregated flight-level) comparisons of fuel burn against data from one major US airline and two major Japanese airlines also showed good agreement with mean errors of −2.62% and 0.42%, respectively. A more detailed presentation of the component errors and uncertainty is contained in the companion SAGE paper (Lee et al., in press).

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