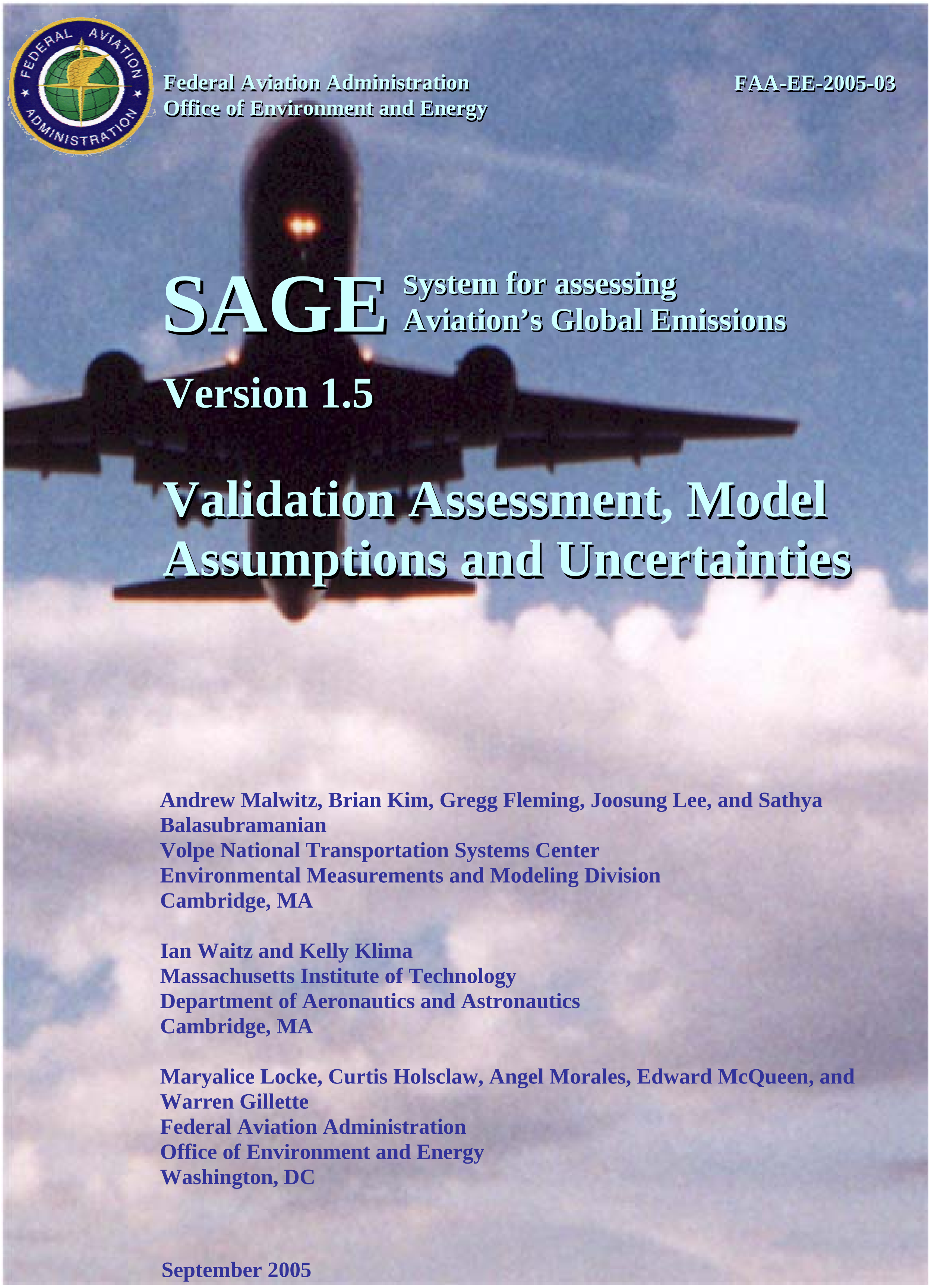

Federal Aviation Administration
Office of Environment and Energy

FAA-EE-2005-03

SAGE System for assessing Aviation's Global Emissions

Version 1.5

Validation Assessment, Model Assumptions and Uncertainties

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September 2005

NOTICE

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE September 2005	3. REPORT TYPE AND DATES COVERED Final Report September 2005

4. TITLE AND SUBTITLE

System for assessing Aviation's Global Emissions (SAGE),
Version 1.5, Validation Assessment, Model Assumptions and Uncertainties

5. FUNDING NUMBERS

FA5N/BS043

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

DOT-VNTSC-FAA-05-13

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

(3) Federal Avitaion Administration
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800 Independence Ave., S.W.
Washington, DC 20591

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

FAA-EE-2005-03

11. SUPPLEMENTARY NOTES: FAA AEE Emissions Division Office Manager: Curtis Holsclaw
FAA AEE Program Manager: Maryalice Locke

12a. DISTRIBUTION/AVAILABILITY STATEMENT: Publicly Available	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The United States (US) Federal Aviation Administration (FAA) Office of Environment and Energy (AEE) has developed the System for assessing Aviation's Global Emissions (SAGE) with support from the Volpe National Transportation Systems Center (Volpe), the Massachusetts Institute of Technology (MIT) and the Logistics Management Institute (LMI). Currently at Version 1.5, SAGE is a high fidelity computer model used to predict aircraft fuel burn and emissions for all commercial (civil) flights globally in a given year. This means that the model is capable of analyzing scenarios at from a single flight to airport, country, regional, and global levels. SAGE is able to dynamically model aircraft performance, fuel burn and emissions, capacity and delay at airports, and forecasts of future scenarios. FAA's purpose in developing SAGE is to provide the international aviation community with a tool to evaluate the effects of various policy, technology, and operational scenarios on aircraft fuel use and emissions. FAA is committed to the continued development and support of SAGE. Although the results from the model have been made available to the international aviation community, SAGE is currently an FAA government research tool and has not been released to the general public.

As part of SAGE Version 1.5 development, this document was developed to provide a detailed description of the model's validation assessment. The assessment was undertaken to quantify the uncertainties of the model's methods, data, and assumptions at both the modular and system levels. It is expected that this assessment will be used as the basis for future SAGE development and validation work.

14. SUBJECT TERMS

SAGE, aircraft, fuel burn, emissions, emissions inventory, aircraft performance, computer model, emissions model, forecasting, model validation, uncertainty assessment, monte carlo simulation

15. NUMBER OF PAGES
34

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

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LIST OF ACRONYMS

AIR	Aerospace Information Report
BACK	BACK Aviation Solutions
BADA	Base of Aircraft Data
CAEP	Committee on Aviation Environmental Protection
CFDR	Computer Flight Data Recorder
ETMS	Enhanced Traffic Management System
FAA	Federal Aviation Administration
FESG	Forecasting and Economics Sub Group
ICAO	International Civil Aviation Organization
INM	Integrated Noise Model
ISA	International Standard Atmosphere
LMI	Logistics Management Institute
LTO	Landing and Takeoff
MIT	Massachusetts Institute of Technology
OAG	Official Airline Guide
OD	Origin-Destination
SAE	Society of Automotive Engineers
SAGE	System for assessing Aviation's Global Emissions
SFC	Specific Fuel Consumption
TAF	Terminal Area Forecast
TOGW	Takeoff Gross Weight
US	United States

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1 INTRODUCTION

The United States (US) Federal Aviation Administration (FAA) Office of Environment and Energy (AEE) has developed the System for assessing Aviation's Global Emissions (SAGE) with support from the Volpe National Transportation Systems Center (Volpe), the Massachusetts Institute of Technology (MIT) and the Logistics Management Institute (LMI). Currently at Version 1.5, SAGE is a high fidelity computer model used to predict aircraft fuel burn and emissions for all commercial (civil) flights globally in a given year. This means that the model is capable of analyzing scenarios at from a single flight to airport, country, regional, and global levels. SAGE is able to dynamically model aircraft performance, fuel burn and emissions, capacity and delay at airports, and forecasts of future scenarios. FAA's purpose in developing SAGE is to provide the international aviation community with a tool to evaluate the effects of various policy, technology, and operational scenarios on aircraft fuel use and emissions. FAA is committed to the continued development and support of SAGE. Although the results from the model have been made available to the international aviation community, SAGE is currently an FAA government research tool and has not been released to the general public.

As part of SAGE Version 1.5 development, this document was developed to provide a detailed description of the model's validation assessment. The assessment was undertaken to quantify the uncertainties of the model's methods, data, and assumptions at both the modular and system levels. It is expected that this assessment will be used as the basis for future SAGE development and validation work. Since the focus of this document is to describe the validation work, technical specifications of the model and outputs are not discussed. Such details can be found in FAA[a, b] 2005.

1.1 Background

The development of SAGE was in part stimulated by the rapid growth in aviation and the need for better emissions modeling capabilities on a global level. According to the "Special Report on Aviation and the Global Atmosphere" by the Intergovernmental Panel on Climate Change (IPCC), air transportation accounted for 2 percent of all anthropogenic carbon dioxide emissions in 1992 and 13 percent of the fossil fuel used for transportation. In a 10-year period, passenger traffic on scheduled airlines grew by 60 percent; and, air travel was expected to increase by 5 percent for the next 10 to 15 years [IPCC 1999]. With this forecast, aircraft remain an important source of greenhouse gases in coming decades [IPCC 1999]. It was also estimated that in 1992, aircraft were responsible for 3.5 percent of all anthropogenic radiative forcing of the climate and (at the time of the report, were) expected to grow to as much as 12 percent by 2050 [IPCC 1999].

The Committee on Aviation Environmental Protection (CAEP) of the International Civil Aviation Organization (ICAO), an organization of the United Nations (UN), has formed several working groups to address aviation environmental emissions. In addition, the UN Framework Convention on Climate Change (UNFCCC) has promoted a series of multilateral agreements that target values of emissions reductions for the primary industrialized nations [IPCC 1999]. However, prior to SAGE, there was no comprehensive, up-to-date, non-proprietary model to estimate aviation emissions at national or international levels that could be used for evaluating policy, technology and operational alternatives.

Although the degree of projected growth of the air transportation industry may be debated, the unique characteristics of the industry, the influence that they may have upon the environment, and the influence that policies may have upon the industry dictates a clear need for a computer model that analysts can use to predict and evaluate the effects of different policy, technology, and operational scenarios.

Past studies on aircraft emissions have resulted in global inventories of emissions by various organizations including the National Aeronautics and Space Administration (NASA)/Boeing [Baughcum[a,b] 1996 and Sutkus 2001], Abatement of Nuisance Caused by Nuisances Caused by Air Transport (ANCAT)/European Commission (EC) 2 group [Gardner 1998], and Deutsche Forschungsanstalt fur Luft- and Raumfahrt (DLR) [Schmitt 1997]. These inventories represent significant accomplishments since they are the first set of “good-quality” global emissions estimates. In this light, SAGE represents the lessons learned from these past studies. Using the best publicly available data and methods, SAGE improves upon these past studies in producing the highest quality emissions inventories to date.

1.2 Objective and Scope

The objective for SAGE is to be an internationally accepted computer model that is based on the best publicly available data and methodologies, and that can be used to estimate the effects on global aircraft fuel burn and emissions from various policy, technology, and operational scenarios. With regard to scope, the model is capable of analyses from a single flight to airport, regional, and global levels of commercial (civil) flights on a worldwide basis.

1.3 Modeling Capabilities

SAGE can generate inventories of fuel burn and emissions of carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NOx), carbon dioxide (CO_2), water (H_2O), and sulfur oxides (SOx calculated as sulfur dioxide, SO_2). The three basic inventories generated by SAGE are: (1) four-dimensional (4D) variable world grids currently generated in a standardized 1^o latitude by 1^o longitude by 1 km altitude format; (2) modal results of each individual flight worldwide; and (3) individual chorded (flight segment) results for each flight worldwide. These outputs and the dynamic modeling environment allow for a comprehensive set of analyses that can be conducted using SAGE.

With the computation modules and the supporting data integrated in a dynamic modeling environment, SAGE provides the capability to model changes to various parameters including those associated with flight schedules, trajectories, aircraft performance, airport capacities and delays, etc. This results in the ability to use SAGE for applications such as quantification of the effects of Communication, Navigation, and Surveillance (CNS)/Air Traffic Management (ATM) initiatives, determining the benefits of Reduced Vertical Separation Minimum (RVSM), investigation of trajectory optimizations, and computing potential emissions benefits from the use of a Continuous Descent Approach (CDA).

1.4 Document Outline

The remainder of this document is organized as follows. Section 2 provides an overview of the entire assessment. Section 3 describes the various databases used in the assessment. This section serves as background material for the subsequent sections. Section 4 describes the assessments conducted on a modular level using data appropriate for each module. In contrast, Section 5 presents the results of assessing the model on a system level through comparisons of overall modeled versus measured flight-level fuel burn data. Section 6 provides the results from uncertainty and error source analyses. Section 7 presents a bulletized list of assumptions used in SAGE. Finally, Section 8 provides concluding remarks related to all of these results.

2 ASSESSMENT OVERVIEW

The main goal in conducting a validation assessment was to establish technical credibility for SAGE Version 1.5 by quantifying the accuracy and uncertainties of the model. This largely involved comparisons of measured versus modeled results and the assessment of uncertainty statistics for the datasets used. Validation data from government and industry sources were used in the analyses.

The assessment involved both modular and system evaluations. Modular evaluations mainly involved the use of aircraft performance and fuel burn-related data. In contrast, system evaluations involved the use of aggregate flight-level fuel burn information, which takes into account the complete movement (or operation) of each flight.

In addition to the accuracy assessments, the validation work included an investigation of the sources of error through Monte Carlo simulations. This study identified some of the major factors that can affect the accuracy of the model.

3 VALIDATION DATA

Several sources and types of validation data were used to assess the accuracy of SAGE. The sources and descriptions of these data are discussed in the following sections to provide a basis for discussions of assessments in the latter sections. Due to confidentiality agreements with some of the sources (e.g., airlines), specifics of some of the data cannot be provided.

3.1 Major United States (US) Carrier

The data provided by a major U.S. Carrier includes both aggregate flight level fuel burn and detailed computer flight data recorder (CFDR) information. The aggregate data covers all carrier flights for the month of October 2000 and includes total fuel burn for each flight. The CFDR data includes high-resolution segment-by-segment aircraft performance, operational, and atmospheric data. Coverage includes eight jet aircraft types including Boeing, Airbus, and Fokker. The data covers the full range of movement (i.e., taxi, takeoff, climbout, cruise, and approach).

3.2 Two Major Asian Carriers

Data from two major Asian carriers is similar to the CFDR data from the major US carrier; it includes aggregate flight-level fuel burn data per flight for the airlines’ flights in the month of October 2003. Included in the data sets are various aircraft types including those from Boeing and Airbus.

3.3 Major European Carrier

Data from a major European Carrier is similar in form, but less detailed than the CFDR data from the US Carrier. Only transatlantic B747-400 flights from October 2000 are included. Data coverage is also limited to the cruise mode.

3.4 Jane’s Aero-Engines

Jane’s Aero-Engines provides detailed specifications on civil and military gas-turbine engines. Data includes but is not limited to engine size and performance metrics including specific fuel consumption (SFC).

3.5 NASA B757-200 Test Aircraft

Data from NASA’s B757-200 test aircraft is similar in form and content to the CFDR data from the major US airline. But unlike the airline, NASA collected the data from test operations that may not reflect “standard” behavior.

3.6 NASA Lift to Drag Ratios (L/D)

L/D values were obtained from the National Aeronautics and Space Administration (NASA) which collected the data from various manufacturers. The data was further verified to be accurate to within 5-10% by a major industry stakeholder.

3.7 Official Airline Guide (OAG) Historical Schedules

The historical OAG data includes 5 years worth of flight schedules from 2000 to 2004. The schedules are obtained from FAA's Office of Aviation Policy and Plans (APO), and includes individual listings of trip legs.

4 MODULAR VALIDATION

Modular validation involves the assessment of individual sub-models to gauge their accuracies and uncertainties.

4.1 Landing and Takeoff (LTO) Profiles

In modeling the LTO modes, data and methods from the Society of Automotive Engineers (SAE) Aerospace Information Report (AIR) 1845 and Eurocontrol's Base of Aircraft Data (BADA) have been combined within SAGE [Bishop 1992 and EEC 2004]. SAE AIR 1845 is the same methodology employed in the FAA's Integrated Noise Model (INM). Although BADA can be used to model all modes, the INM data and methods were implemented for LTO modeling because INM has been in existence much longer than BADA, and has not only been extensively validated, but is internationally recognized and accepted as well [Flathers 1982].

Using these methods, SAGE Version 1.5 currently assumes full power takeoff. Methodologies will be investigated for incorporation into future versions of SAGE that will allow for modeling of derated takeoffs, which are now commonly used by the airline industry primarily for repair and maintenance benefits.

SAE AIR 1845's contribution to the SAGE LTO methodology is through the 1845 procedures and takeoff thrust calculations. This results in LTO profiles that are close to those represented by SAE AIR 1845/INM. Figure 1 shows LTO profiles generated for a B727-200. For takeoff, SAGE produces a slightly faster climb (i.e. steeper curve). This is mainly due to the energy share factor used. The energy share factor represents how the excess power generated by aircraft engines is allocated to changing the potential energy versus kinetic energy of the airplane. If the energy share factor is equal to 1, all excess power of the engines goes to changing potential energy. For fast acceleration, it is usually set to around 0.3 which indicates that the majority of the available power is devoted to a change in speed. The energy share factor remains almost constant for SAGE. But for INM, it is programmed to decrease (less energy being used for potential energy change) with altitude increase. This is why it takes longer for the INM profile to achieve the same altitude increase. Other differences in takeoff performance are attributed to different aerodynamic coefficients used by the two models.

During approach and landing, the SAGE profile overlaps precisely with the SAE AIR 1845/INM profile because both use a 3-degree gliding slope as indicated in Figure 1. In SAGE, 3-degree and 5-degree glide slopes are used for jets and turboprops, respectively.

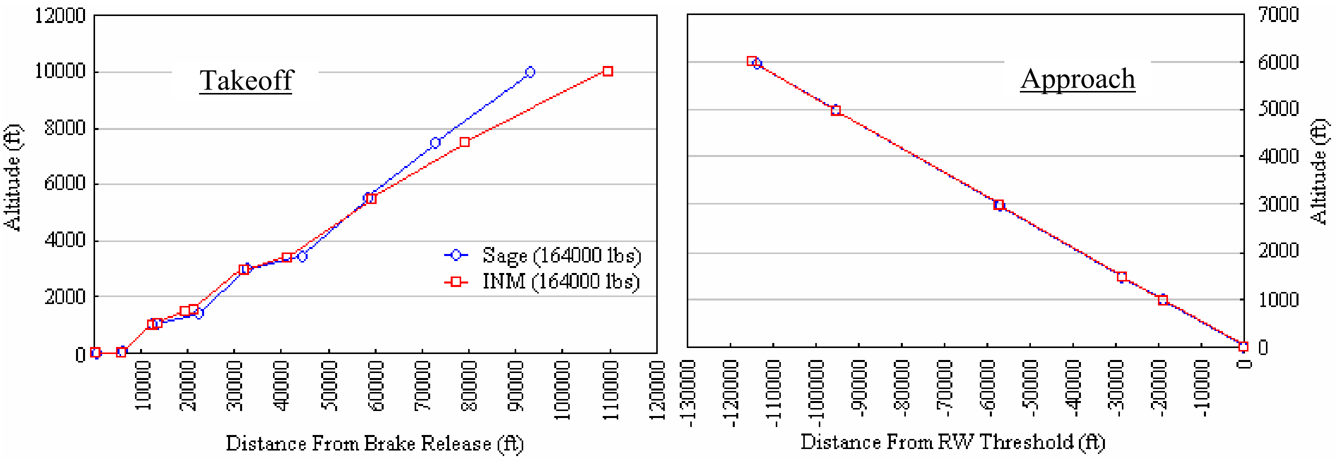

Figure 1. SAGE Takeoff and Approach Profiles in Comparison to INM Standards for a B727-200

Figure 2 shows the horizontal distances traversed during take-off and climb up to 10,000 ft for various aircraft types. The INM and SAGE results agree with 10-20% differences with no apparent bias in either direction. These uncertainties are mainly due to the fact that airlines use slightly different LTO procedures depending on various factors including aircraft types, airport configurations, traffic loads, and weather conditions.

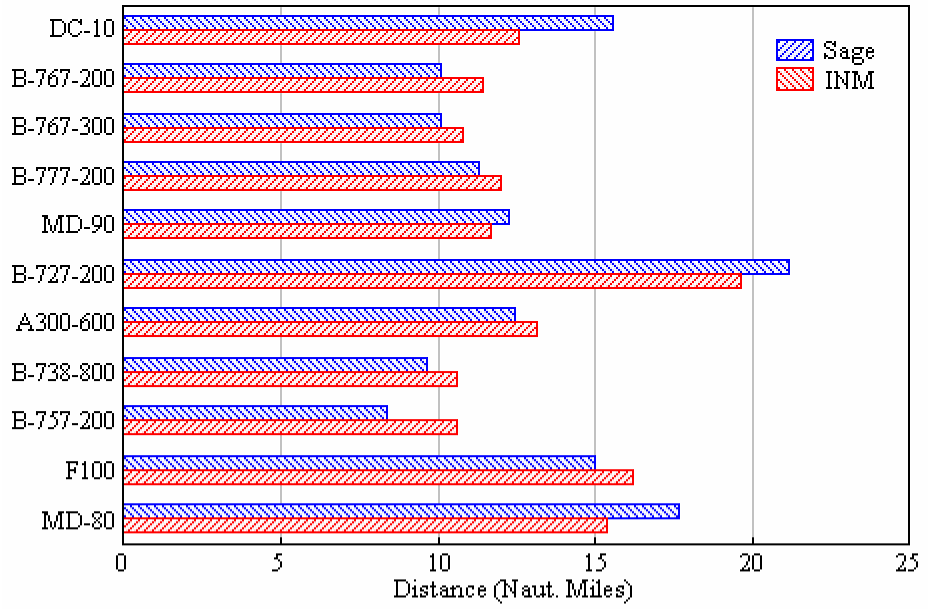

Figure 2. Comparison of Horizontal Distance Traversed During Take-off and Climb

4.2 Aerodynamic Component

Figures 3 and 4 show SAGE L/D curves (generated using BADA data) as a function of the lift coefficient (C_L) for an A320-100 and B747-400, respectively, at a cruise altitude of 35,000 feet. The general shape compares well with published data [Cumpsty 1997]. However, the maximum L/D values are lower than the NASA industry data. At flight speeds of Mach 0.82, the maximum L/D is roughly 14.8 for A320-100 and 15.9 for B747-400, as shown in the figures. For the same airframes and cruise Mach number, L/D values in the NASA database are 16.5 and 17.7, respectively. At present, it is difficult to make a more rigorous assessment because the BADA lift curve is insensitive to both flight speed and ambient temperature changes. This is due to the fact that BADA has only a fixed set of drag coefficients, which are mainly tuned for best cruise performance. In order to simulate flight altitude, speed, and ambient temperature effects more accurately, it may be necessary to introduce a correction factor for the drag coefficients in a future version of SAGE.

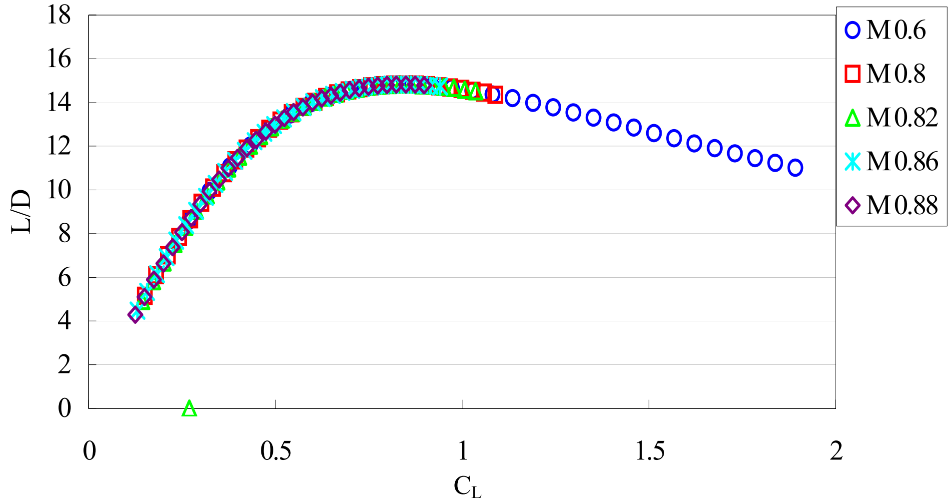

Figure 3. SAGE Aerodynamic Component Assessment of A320-100 at 35,000 ft

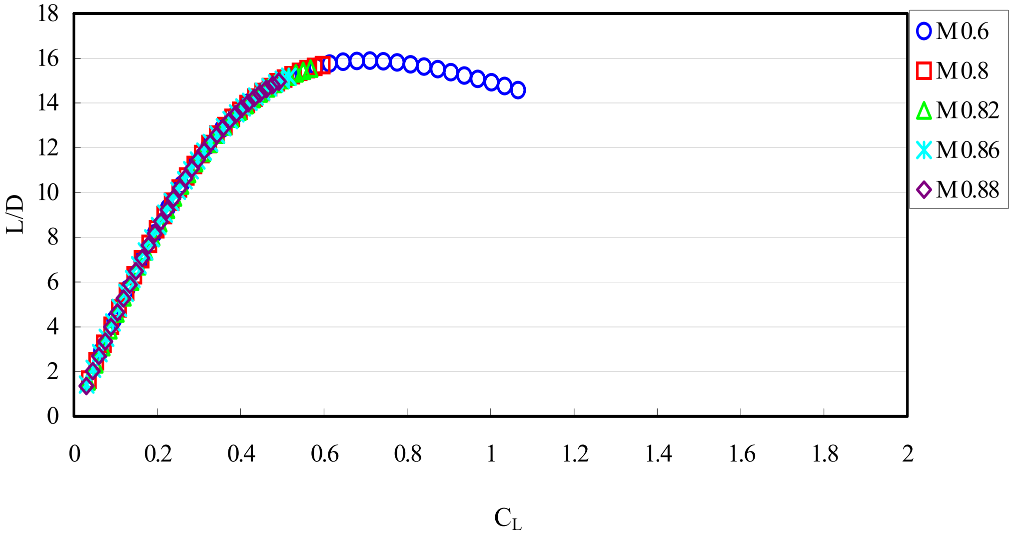

Figure 4. SAGE Aerodynamic Component Assessment of B747-400 at 35,000 ft

A comparison of the L/D values for various aircraft types used in BADA (SAGE) versus those from NASA are shown in Figure 5. Analysis of the data shows that the SAGE-generated L/D values are within ±14% of the NASA data with 1σ confidence.

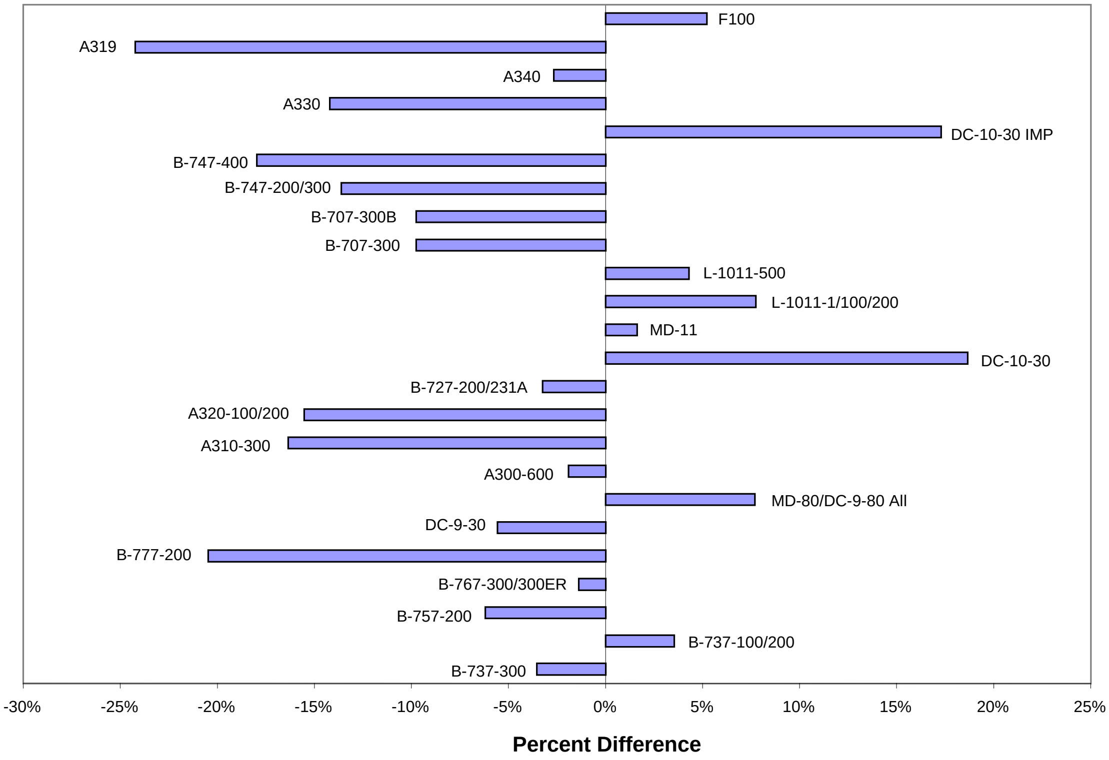

Figure 5. Comparison of BADA L/D Values to NASA-Industry Provided Data

4.3 Fuel Flow Component

Accuracy of the fuel flow component directly impacts accuracy of SAGE outputs. Ten high-resolution flight datasets from a major US carrier (i.e. two flights for each of five aircraft types) were used for comparisons covering all modes of flight and movement. Figure 6 shows that SAGE accurately predicts the fuel flow for the ten flights during the LTO and cruise modes with relevant statistics presented below:

- Mean (% difference) = 6.95%
- Standard deviation of errors = 36.7%
- Sample points = 1449

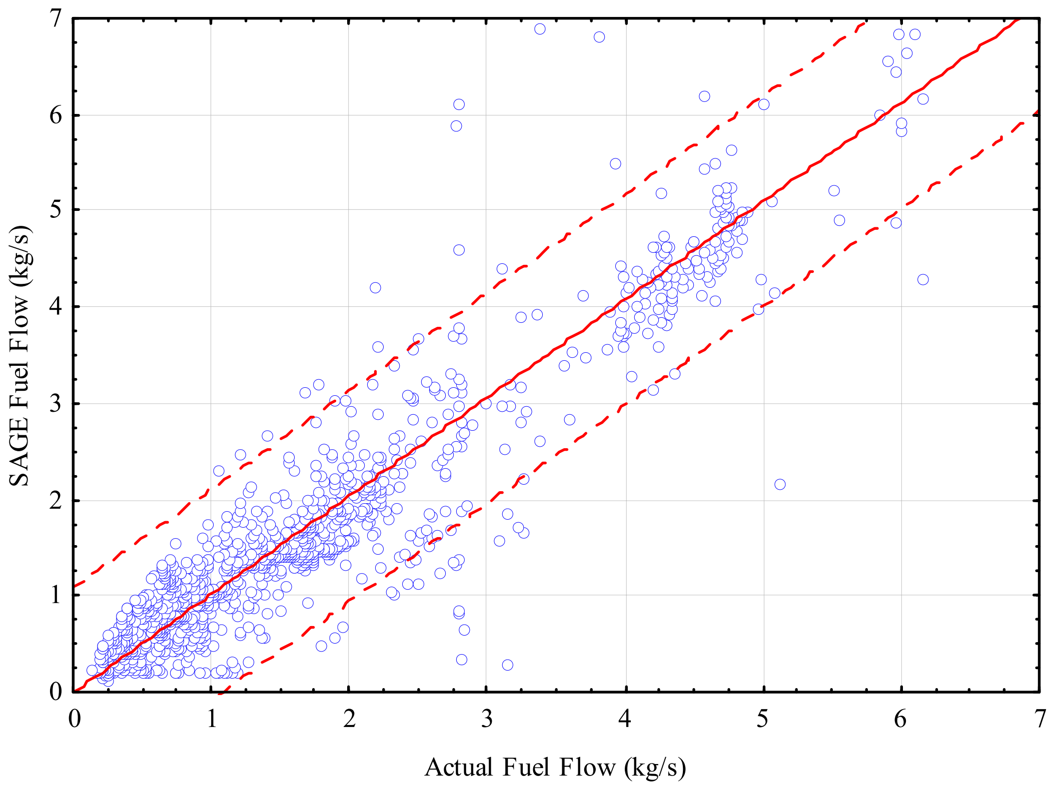

Figure 6. SAGE Fuel Flow Comparisons Against Data from a Major US Carrier

In addition to the comparisons against the major US carrier, data from NASA's B757-200 test aircraft were also used for comparisons. Figure 7 shows the comparisons against two NASA B757-200 flights with the resulting statistics presented below:

- Mean (% difference) = -0.24%
- Standard deviation of errors = 37.3%
- Sample points = 3537

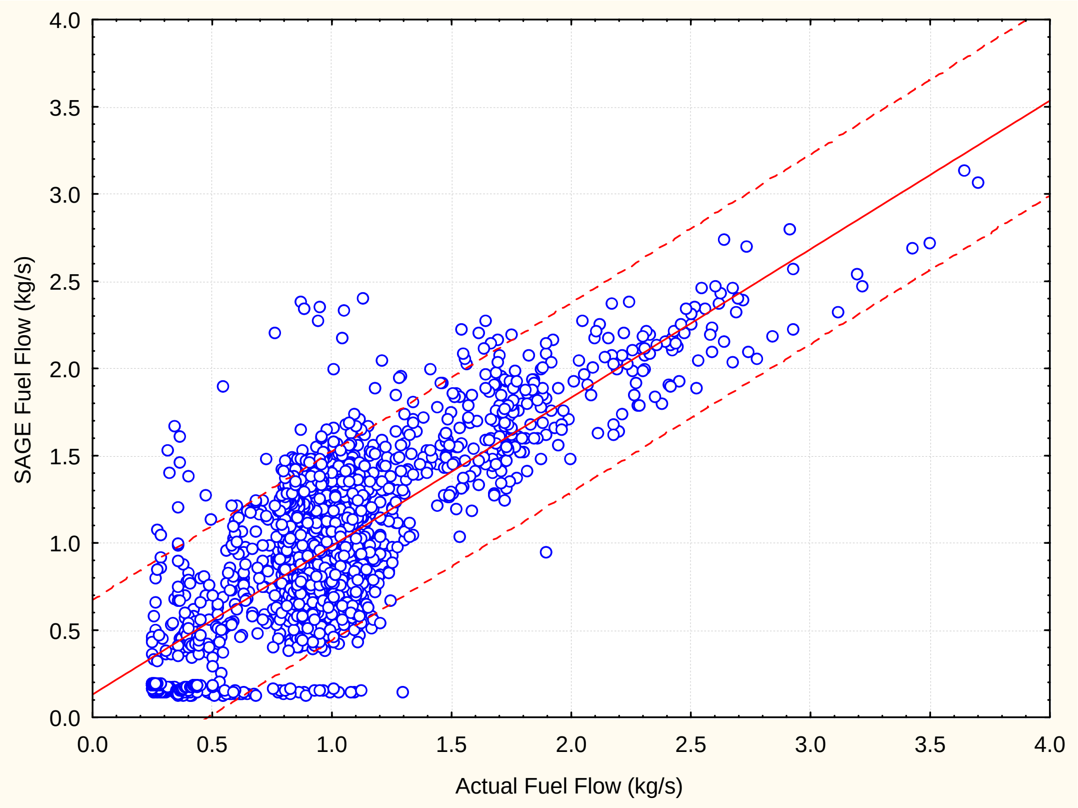

Figure 7. SAGE Fuel Flow Comparisons Against Data from NASA

Both sets of comparisons (i.e., against data from the major US airline and NASA) show excellent agreement on an overall basis. And there does not appear to be any noticeable bias (i.e., no over or under-prediction). Some of the scatter in the data, especially at low fuel flows can be attributed to the fidelity of BADA. The BADA fuel flow model used in SAGE is a polynomial function of flight speed and altitude. However, the minimum fuel flow associated with low engine power settings is only a function of altitude, the simplicity of which causes the inaccuracies during the idle and taxi modes. Also, ambient temperatures currently have no direct effect on fuel flow. In practice, as ambient temperature decreases, engine efficiency increases and fuel consumption decreases. The quantitative relationship between ambient temperature and engine fuel consumption will need to be investigated during development of future versions of SAGE. However, these comparisons should currently provide a high degree of confidence in the BADA fuel flow predictions on an overall basis.

A more specific investigation of the fuel flow component involves analyzing the cruise SFC data used in SAGE. Figure 7 shows a plot of the SAGE cruise SFC values versus those obtained from Jane's Aero-Engines [Gunston 2000]. The sample engine types were selected based on popularity in the world fleet and also based on equivalently matching the types between the default engines in BADA and those in Jane's Aero-Engines. The % errors indicate that most engines appear to be within 10% difference in SFC with a couple over 20%. Although the majority of these differences are small, they will need to be further investigated, especially as BADA experiences further improvements to its fuel flow modeling capabilities.

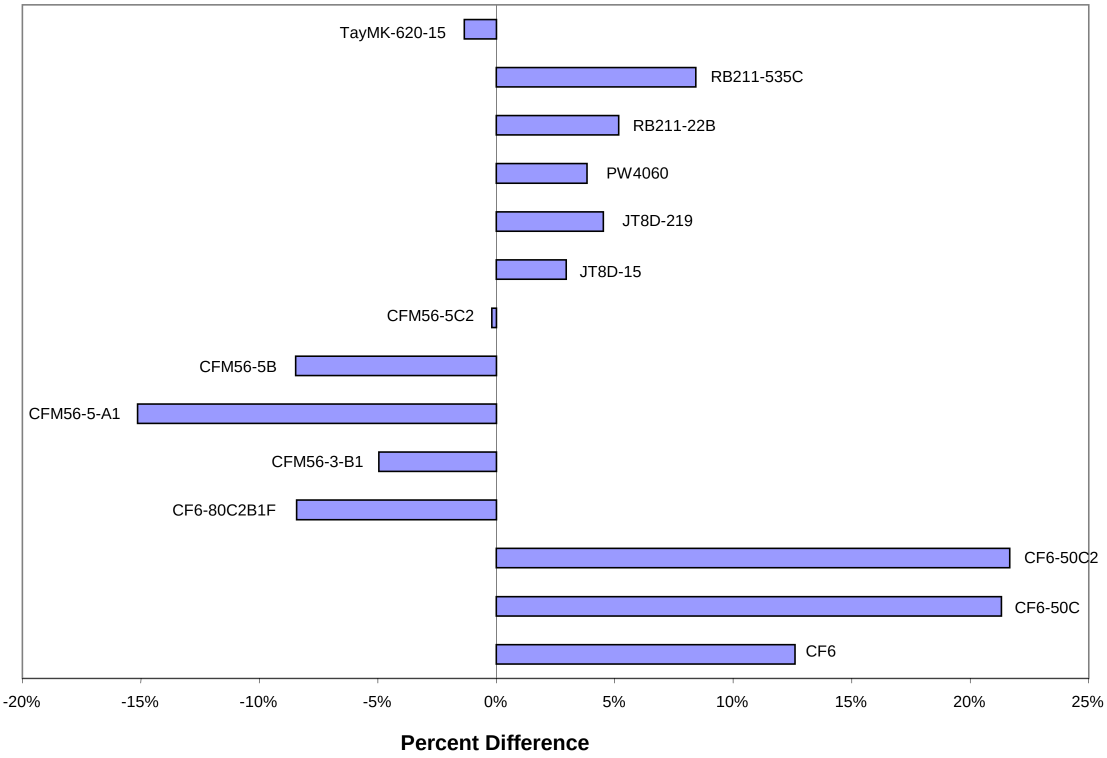

Figure 8. Comparison of BADA SFC Values to Published Data from Jane's Aero-Engines

4.4 Forecasted Schedules

In SAGE, future schedules can be generated based on growth factors and assumptions from the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP) Forecasting and Economics Subgroup (FESG) and the FAA's Terminal Area Forecast (TAF). The FESG data provides growth in regions outside of the US and the TAF provides growth within the US. These data and methods are internationally accepted and commonly used in forecasting flights at various levels including airport, country, region, and global. SAGE currently uses a week's worth of OAG flights to obtain a future year's worth of flights in order to determine ratios of future and base loadings of fuel burn and emissions. To obtain future magnitudes of these loadings, the ratios are applied to the more accurate historical inventory(ies) developed for the entire base year.

Because forecasting is an inexact science involving many assumptions, any attempts to validate the results will be dubious. However, a cursory assessment was conducted to gauge the impact of the forecasting methodology. The assessment was based on comparisons of actual (historical) OAG schedules to forecasted schedules. The historical scheduled number of flights are shown in Table 1 and the corresponding forecasted flights are shown in Table 2.

Table 1. Historical Number of OAG Global Flights

Day	2000	2001	2002	2003	2004
May 29	76890	80378	76362	71996	64482
May 30	79103	81400	75872	73337	64819

May 31	80005	81317	77186	60907	73884
June 1	78323	82128	62539	64077	77197
June 2	79636	66389	65471	73521	77996
June 3	65577	68432	74915	72835	78395
June 4	68563	78768	75090	73890	79670
Total		**538812**		**490563**	**516443**

Table 2. Forecasted Number of OAG Global Flights

Day	2000	2001	2002	2003	2004
May 29		76729		76609	76798
May 30		78983		76101	76294
May 31		79870		77459	77629
June 1		78672		62741	62896
June 2		79995		65669	65848
June 3		65835		75135	75347
June 4		68845		75308	75507
Total		**528929**		**509022**	**510319**

Forecasts for 2001 were developed using the 2000 base data and forecasts for 2003 and 2004 were developed using the 2002 base data. Although a 2002 forecast could have been developed using the 2000 base FESG and TAF data, it would have been improper since the effects of September 11, 2001 (9/11) would have caused discrepancies in the analysis. But the forecasts for 2001 are considered viable for the analysis because the forecasted days (May 29 to June 4) occur before 9/11.

The data in Tables 1 and 2 cannot be compared directly on a day-to-day because the days of the week shift from year to year. That is, when 2000 and 2002 are used as baselines, the forecasted data will correspond directly to the order of the days in the baseline years. As a result, the days of the week must first be aligned so that daily variations are not a source of confounding errors. Table 3 shows the historical days of the week for each year and Table 4 shows a mirroring of the baseline's days to the forecasted years.

Table 3. Historical Days of the Week

Day	2000	2001	2002	2003	2004
May 29	Monday	Tuesday	Wednesday	Thursday	Saturday
May 30	Tuesday	Wednesday	Thursday	Friday	Sunday
May 31	Wednesday	Thursday	Friday	Saturday	Monday
June 1	Thursday	Friday	Saturday	Sunday	Tuesday
June 2	Friday	Saturday	Sunday	Monday	Wednesday
June 3	Saturday	Sunday	Monday	Tuesday	Thursday
June 4	Sunday	Monday	Tuesday	Wednesday	Friday

Table 4. Forecasted Days of the Week

Day	2000	2001	2002	2003	2004
May 29		Monday		Wednesday	Wednesday
May 30		Tuesday		Thursday	Thursday
May 31		Wednesday		Friday	Friday
June 1		Thursday		Saturday	Saturday
June 2		Friday		Sunday	Sunday
June 3		Saturday		Monday	Monday
June 4		Sunday		Tuesday	Tuesday

In order to match the historical days of the week, the forecasted data in Table 2 were rearranged as shown in Table 5.

Table 5. Rearranged Forecasted Number of OAG Global Flights

Day	2000	2001	2002	2003	2004
May 29		78983		76101	62896
May 30		79870		77459	65848
May 31		78672		62741	75347
June 1		79995		65669	75507
June 2		65835		75135	76798
June 3		68845		75308	76294
June 4		76729		76609	77629
Total		**528929**		**509022**	**510319**

The resulting percent differences between Tables 1 and 5 are shown in Table 6.

Table 6. Percent Differences of Historical and Forecasted OAG Global Flights

Day	2000	2001	2002	2003	2004
May 29		-1.74		5.70	-2.46
May 30		-1.88		5.62	1.59
May 31		-3.25		3.01	1.98
June 1		-2.60		2.48	-2.19
June 2		-0.83		2.20	-1.54
June 3		0.60		3.40	-2.68
June 4		-2.59		3.68	-2.56
Total		**-1.83**		**3.76**	**-1.19**

The differences shown in Table 6 appear to indicate that the forecasted flights agree very well with historical OAG flight data, at least on aggregated levels (i.e., daily and weekly). Because forecasting of fuel burn and emissions involves accumulating all results for the week rather than analyzing individual days, the percent differences (-1.93%, 3.76%, and -1.19%) are the more interesting results. The positive percent differences for 2003 may be indicative of optimism in aviation growth from CAEP (FESG) and/or FAA (TAF) after 9/11. It could also signify a slight underestimation in the OAG schedules themselves after 9/11 which would have meant more unscheduled flights. In any case, the daily and weekly differences are still very small, and therefore, provides some confidence in the use of the SAGE forecasting methods and data.

These comparisons provide an overview of the accuracy of the forecasting global flights. Future validation work may involve refinements to these comparisons by including categorizations of flights by carrier, equipment type, and origin-destination (OD) pairs. In addition to these categories, more years and different days/weeks could also be compared as well.

5 SYSTEM VALIDATION

System validation examines the errors and behavior of the model in predicting fuel burn results on an aggregate level. Therefore, the assessment implicitly includes evaluations of aircraft trajectory data as well as performance and fuel burn.

5.1 Fuel Burn Comparisons Against Data from a Major U.S. Carrier

SAGE fuel burn results have been computed using over 44,000 flights that appear in each of Enhanced Traffic Management System (ETMS) and OAG flights for October 2000 that were matched to the major US airline's flights. Errors (the percentage difference) were computed between SAGE fuel burn outputs and actual values. Figure 8 represents a histogram of the error percentage (the percentage difference between the SAGE calculated fuel burn and actual fuel burn). Table 7 displays a few statistical values for the error: mean error, an average of all error percentages; standard error, the standard deviation of the mean which represents the reasonable uncertainty of the mean; the median percentage error value; standard deviation of errors, the standard deviation of all the percentage errors; a count of the number of data points; and the 95% confidence interval. The mean and standard deviation of errors are –0.25% and 13.04%, respectively, when comparing ETMS flights to actual values, and –11.32% and 10.66% when comparing OAG flights to actual values. This indicates that SAGE can predict fleet fuel burn with less than 1% error on average for ETMS based flights, and around 10% for OAG based flights. However, SAGE does not report ETMS and OAG flights in separate inventories such that overlaps would occur. Rather, they are combined with ETMS flights taking precedence over OAG-based flights. There, OAG flights are used to supplement flights not covered by ETMS. Figure 9 andTable 7 show the errors computed between the combined data set of ETMS and OAG flights (over 59,000 flights) and those from the major US carrier. The mean and standard deviation of errors are –2.62% and 13.69%. This demonstrates that SAGE can predict fleet fuel burn with less than 5% error on average.

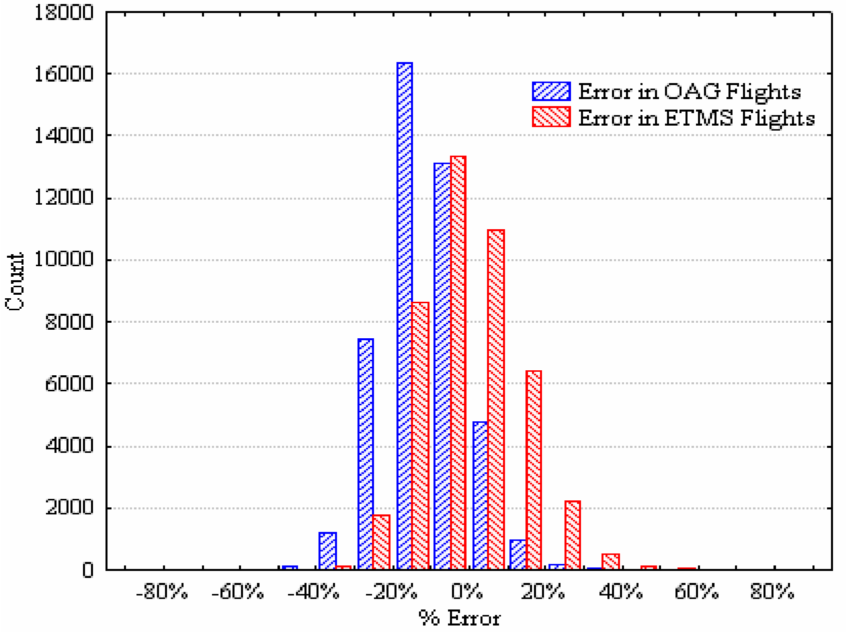

Figure 9. ETMS and OAG Fuel Burn Comparisons to a Major US Carrier for October 2000

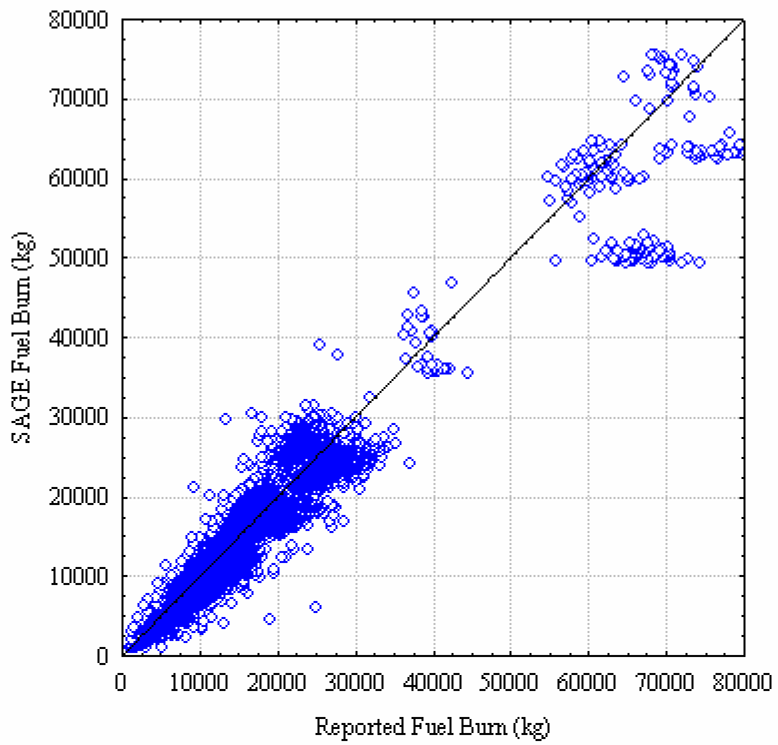

Figure 10. Reported (From Major U.S. Carrier) versus SAGE Fuel Burn

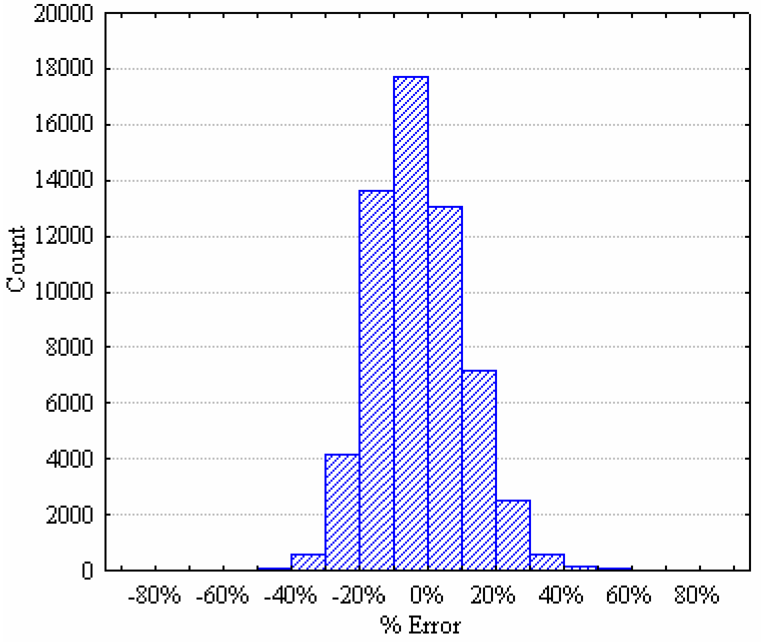

Figure 11. Combined ETMS and OAG Fuel Burn Comparisons with a Major US Carrier's Data

Table 7. System Error Statistics for ETMS, OAG, and Combined Flights (Major US Carrier)

Statistic	ETMS Flights	OAG Flights	SAGE (ETMS/OAG) Flights
Mean Error	-0.25%	-11.32%	-2.62%
Standard Error	0.06%	0.05%	0.06%
Median	-1.34%	-11.74%	-3.79%
Standard Deviation of Errors	13.04%	10.66%	13.69%
Count	44,208	44,280	59,627
95% Confidence Level	0.12%	0.10%	0.11%

5.2 Fuel Burn Comparisons Against Data from Two Major Asian Carriers

The same analysis was made for the data obtained from two major Asian carriers. In all, over 19,000 flights with flight level fuel burn data were compared against the fuel burn amounts from the combined ETMS/OAG SAGE data sets. Figure 11 displays SAGE versus reported fuel burn scatter plot, and Figure 12 and Table 8 show the errors computed between the combined data set of ETMS and OAG flights and those from the major Asian carriers. The mean and standard deviations of the errors are 0.42% and 21.50% respectively, which demonstrates a consistency with the error from the major American carrier data.

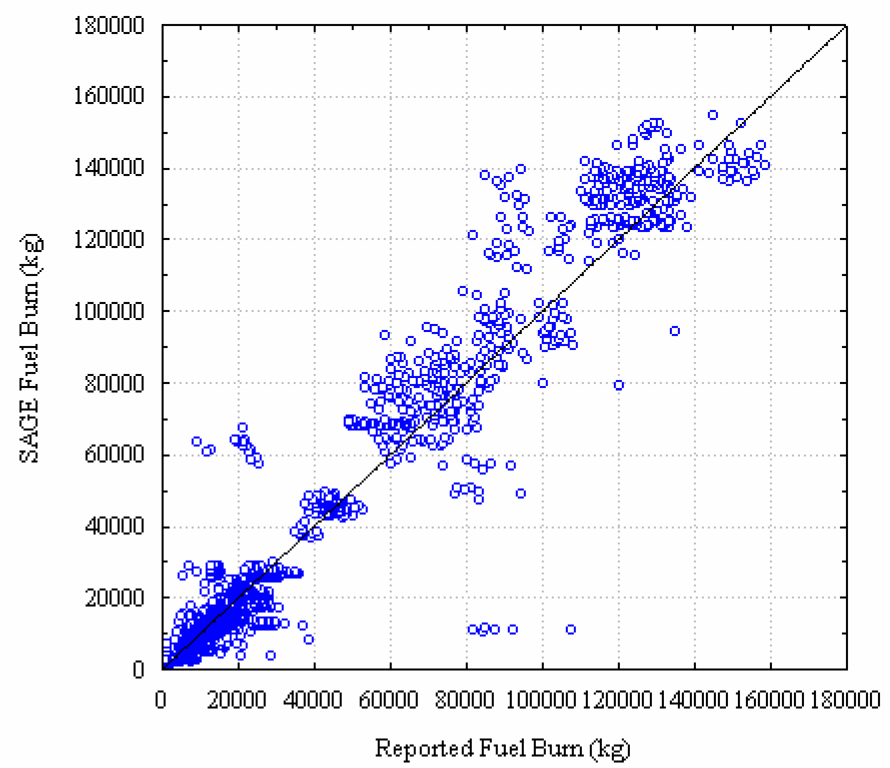

Figure 12. Reported (From Two Major Asian Carriers) versus SAGE Fuel Burn

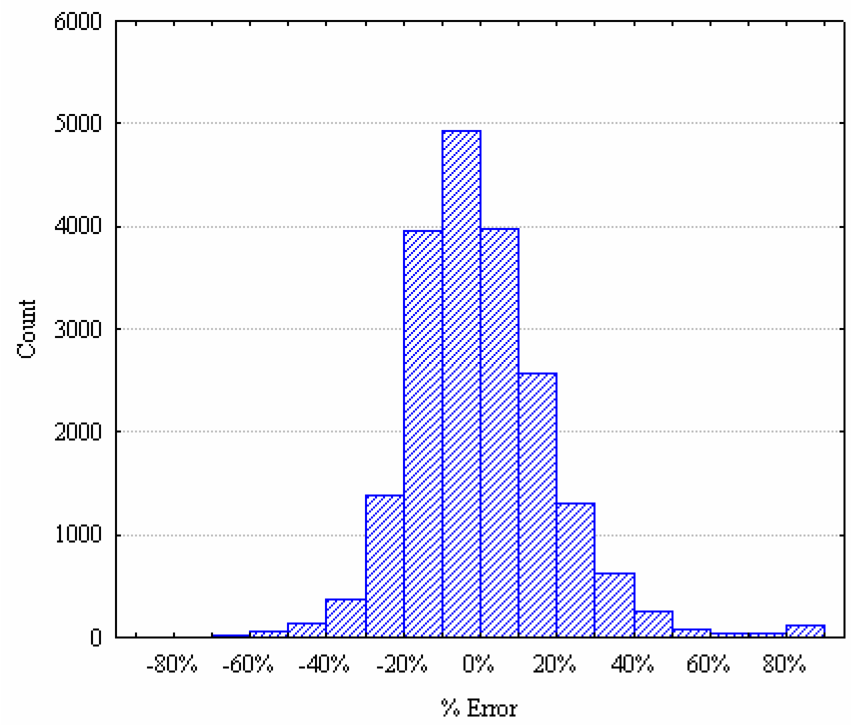

Figure 13. SAGE Fuel Burn Error Compared to Two Major Asian Carriers

Table 8. System Error Statistics for SAGE Flights (Two Major Asian Carriers)

Statistic	SAGE (ETMS/OAG) Flights
Mean Error	0.42%
Standard Error	0.15%
Median	-1.91%
Standard Deviation of Errors	21.50%
Count	19888
95% Confidence Level	0.30%

5.3 Specific Issues Within System Validation

As can be seen, the largest area in need of improvement is fuel burn calculations based solely on OAG flight. The errors with the OAG flights may be due to the created flight tracks and speed data. Also, as Figure 10 indicates, errors appear to be greater for shorter range flights. There could be several reasons for this including a greater degree of aircraft substitutions for shorter-range aircraft types since BADA and SAE AIR 1845 coverage is not as abundant for them. Also, trajectory modeling (i.e., for OAG flights) is also not likely to be as accurate for shorter range flights.

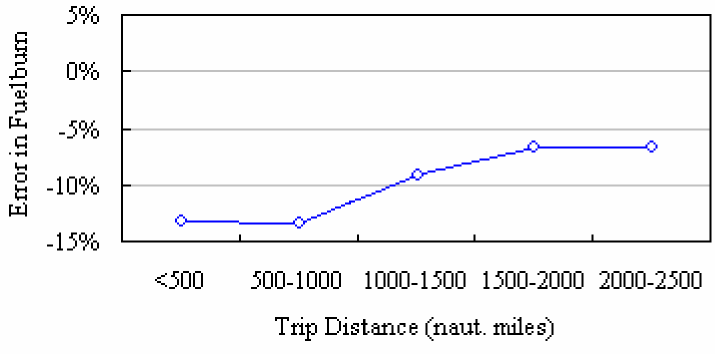

Figure 14. Error Associated With Varying Trip Distances in OAG

Another area affecting aggregate fuel burn is the weather assumption. As will be discussed, SAGE assumes International Standard Atmosphere (ISA) conditions with standard lapse rates and no winds. A preliminary study was conducted using a previous version of SAGE showing the effects of including actual meteorological data (including winds) and the incorporation of transonic drag rise (compressibility effects). Complete meteorological data was obtained for October 5, 2000, and the fuel burn data from the major US carrier (1306 flights for the particular day) were used as the basis for comparisons. The results of the analysis are shown in Table 8. On an aggregate level, the error reduced from –7.87% to 2.70% [Klima 2005]. This demonstrates that a noticeable amount of the error (or at leas the scatter) within SAGE could be related to unknown weather conditions.

Table 9. System Error Statistics with/without Weather and Transonic Drag

Statistic	Without Weather/Transonic Drag	With Weather/Transonic Drag
Mean Error	-7.87%	2.70%
Standard Deviation of Errors	13.75%	12.59%
Count	1306	1306

6 UNCERTAINTY AND ERROR SOURCE ANALYSIS

The objective of this section is to identify the most influential sources of error in SAGE and to quantify the magnitude of their impact on system-level performance. The sources that have the largest impact on global fuel burn and emissions errors are examined. A specific assessment of winds were conducted and then a Monte Carlo simulation was performed to determine relative contributions of error by various parameters.

6.1 Winds

As discussed in Section 5.2, a large portion of fuel burn error can be attributed to the fact that SAGE Version 1.5 assumes no winds aloft. In order to quantify the effects of the no wind assumption, 34 flights from a major European carrier’s B747-400 CFDR data in October 2000 were randomly selected. Detailed position, actual takeoff gross weight (TOGW), winds aloft, and ambient temperature information were obtained from the sample. To determine the effects of the no wind assumption, actual position and TOGW were used as input to SAGE, and errors in flight speed were calculated. Figure 11 shows that fuel burn error is highly correlated with flight speed error as indicated by the correlation factor of 0.87. Although the correlation is for both wind and temperature, wind is considered to be a much more significant source of error than temperature.

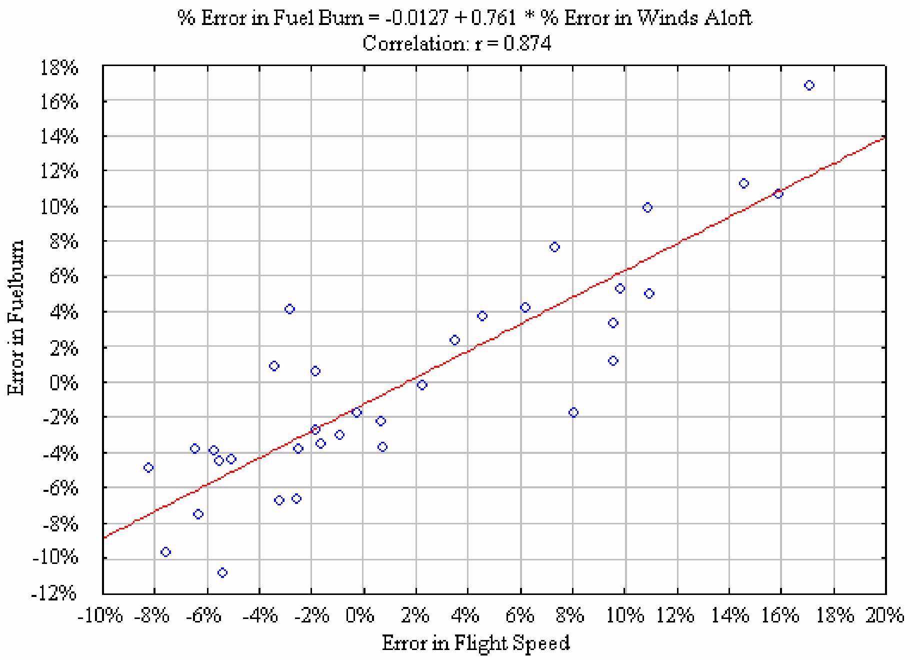

Figure 15. Contribution of Uncertainty in Winds Aloft to Total Error in Fuel Burn (B747-400)

6.2 Monte Carlo Simulation

Monte Carlo simulations were conducted to help explain the unique contribution of each key input uncertainty to total error [Lee 2005]. In order to do this, the match Monte Carlo simulated distributions of errors must match the error distributions generated in Section 5. That would show that the system-level errors associated with the simulations are consistent with SAGE results and that the choice of uncertainties modeled in the simulations are representative of those in SAGE.

As previously discussed, the most influential uncertainties for global fuel burn results are: use of standard day ambient temperature, not correcting for winds aloft, uncertain aerodynamic and engine performance, and simplified assumptions about aircraft takeoff weight and flight speed. Additional uncertainties associated with the use of OAG-based flight trajectories are considered only for OAG flights. Uncertainties in emissions estimated are also significantly influenced by uncertainties in emissions indices.

Table 10. Key Input Uncertainties for Monte Carlo Simulation on SAGE Flights
(Dispersion track and cruise altitude applicable to OAG flights only)

Parameter	Uncertainty Estimate	Approximate Distribution
Dispersion Track (OAG Only)	±5% of Flight Time (1σ)	Normal
Cruise Altitude (OAG Only)	±3000 ft (1σ)	Discrete Normal
Ambient Temperature at Cruise	3.3 K (1σ)	Normal (One Sided)
Winds Aloft	±12.5 m/s (1σ)	Normal
Aerodynamic Drag	±14% (1σ)	Normal
Engine Fuel Consumption	±11% (1σ)	Normal
Takeoff Weight	±13% (1σ)	Normal

The values for the key uncertainties are randomly generated based on a normal distribution where their default values as used in SAGE are assumed to be the mean.

Cruise altitude deviations from the mean altitude are generated using a discrete normal distribution with a 1000 foot increment. Ambient temperature deviations from the ISA temperature are generated using a one-sided normal distribution in between 0K and 3.3K (1σ). This is because the Boeing analysis showed that at cruise altitudes, temperature deviations occur only above the standard day temperature [Daggett el al. 1999]. Table 9 shows seven key uncertainties with their estimated standard deviations for a simulation on SAGE flights. These standard deviation estimates are based on observations and experiences in modeling these flights within SAGE [Lee 2005]. The actual magnitudes of these estimates are not as important as their relative differences.

All 11 aircraft types of the major US carrier (e.g. B727-200, B737-800, B757-200, B767-200, B767-300, B777-200, A300-600, DC10, MD80, MD90 and F100) are used. Dispersion track and cruise altitude uncertainties are included only with a simulation on OAG flights to account for the additional uncertainty caused by artificial flight trajectories used.

Based on these inputs, 3000 iterations were performed for both sets of ETMS and OAG flights. Figure 12 shows the simulation results for the fuel burn of ETMS flights. The difference between the nominal fuel burn (i.e. with mean input values) and mean fuel burn (i.e. average fuel burn for the distribution) was calculated. The difference was -3.9% with standard deviation of 16.5%. This accounts for about 90% of the total variance in ETMS fuel burn errors in SAGE. Figure 13 shows the simulation results for the fuel burn of OAG flights where the difference between nominal fuel burn and mean fuel burn was -5.1% and standard deviation was 17.0%. This accounts for about 95% of the total variance in OAG fuel burn errors in SAGE. Note that these Monte Carlo simulations converge with less than 2% error.

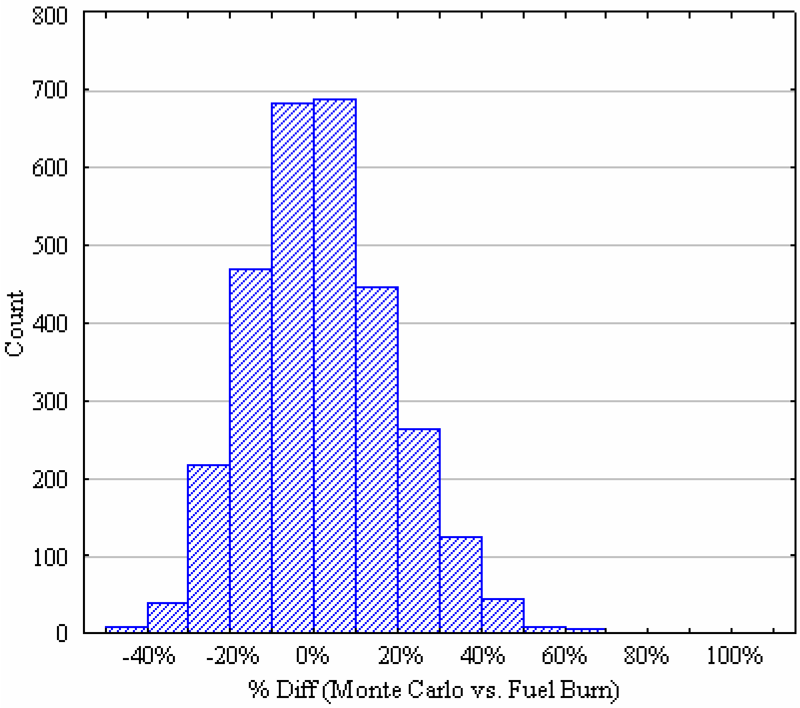

Figure 16. Monte Carlo Simulation Results on ETMS Trajectories

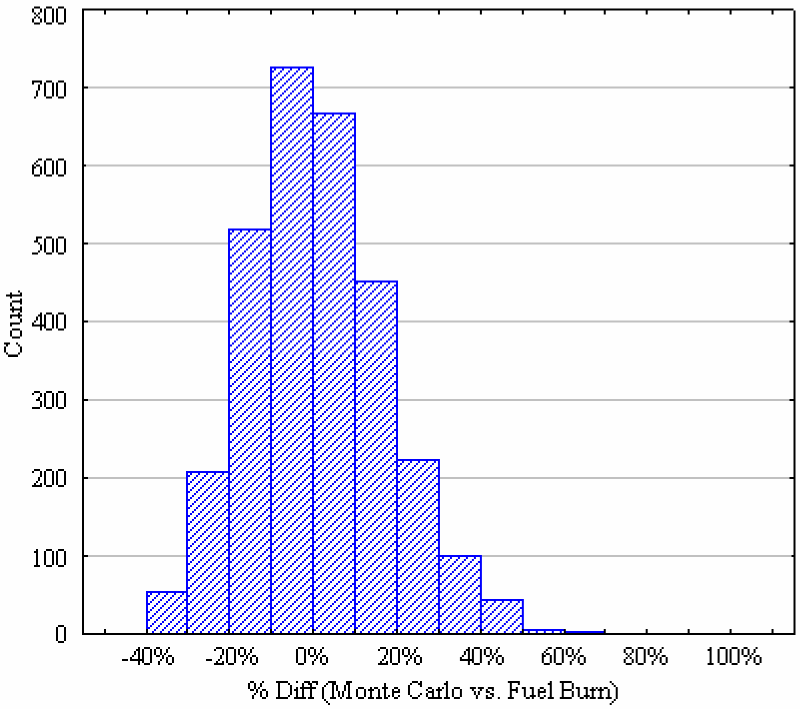

Figure 17. Monte Carlo Simulation Results on OAG Trajectories

The error distributions of the simulation results based on 11 aircraft types (B727-200, B737-800, B757-200, B767-200, B767-300, B777-200, A300-600, DC10, MD80, MD90 and F100) were shown to compare well to the error distributions of the over 44,000 ETMS and OAG flights analyzed in Section 5. This indicates the applicability of the Monte Carlo simulations to help determine the biggest contributors to the overall errors within SAGE. The same type of uncertainty roll-up for all aircraft types in SAGE was conducted. The difference between nominal fuel burn and mean fuel burn was -4.4% with standard deviation of 16.0%. This result showed that the 11 aircraft types represent well the aircraft performance characteristics and associated uncertainties in the full SAGE fleet.

6.3 Understanding Variance of Error

In order to quantify the unique contribution of the key uncertainties to total error, the fuel burn results of the Monte Carlo simulations are regressed on the input values. Both the input and the output values are standardized (i.e. z-scored) by subtracting the mean from the respective value and dividing the difference by the standard deviation. Tables 10 and 11 show the regression results for ETMS and OAG flights. The magnitude of the beta coefficients shows the relative contribution of each key uncertainty in the prediction of fuel burn.

Table 11. Regression Among the Monte Carlo Simulation Variables for ETMS Flights

Parameter	Beta	Std. Error	Contribution to Var.
Engine Fuel Consumption	0.480	0.00271	29.4%
Aerodynamic Drag	0.592	0.00313	44.7%
Takeoff Weight	0.374	0.00312	17.9%
Winds Aloft	0.249	0.00271	7.91%
Ambient Temperature at Cruise	0.024	0.00271	0.075%

R^2=.986 Adjusted R^2=.986 n=3000
F(5,2994)=26848. $p<0.0001$ Std. Error of estimate: .12113

where:
Beta = standardized regression coefficient
Standard Error = standard deviation of the estimated coefficient or relationship
R^2 = the coefficient of determination (variance in the dependent variable that is explained by the independent variables)
Adjusted R^2 = R^2 adjusted by the degrees of freedom of both the numerator and the denominator
F = F-statistic (for the regression result to be significant)
p = p-value (probability for the regression result to be false)

Table 12. Regression Among the Monte Carlo Simulation Variables for OAG Flights

Parameter	Beta	Std. Error	Contribution to Var.
Engine Fuel Consumption	0.480	0.00271	24.0%
Aerodynamic Drag	0.592	0.00313	36.5%
Takeoff Weight	0.374	0.00312	14.6%
Winds Aloft	0.249	0.00271	6.46%
Ambient Temperature at Cruise	0.024	0.00271	0.061%
Cruise Altitude	-0.111	0.00374	1.28%

Dispersion Track	0.406	0.00374	17.1%

$R^2=.968$ Adjusted $R^2=.967$ $n=3000$
$F(7,2992)=9991.7$ $p<0.0001$ Std. Error of estimate: .16670

For ETMS flights, the uncertainties in engine and aerodynamic performance are the largest sources of error, together accounting for over 70% of the total variance. The takeoff weight and winds aloft uncertainties account for 17.9% and 7.9%, respectively. The ambient temperature uncertainty accounts for less than 1% of the error which helps to reaffirm the earlier comment in Section 6.1 that temperature is likely a smaller source of error than winds. However, on an individual flight basis on a specific day or in a region, the ambient temperature uncertainty can possibly be large and therefore become a noticeable source of fuel burn error. For OAG flights, the engine and aerodynamic performance uncertainties also account for the largest fraction of the error, 24.0% and 36.5% each. The takeoff weight uncertainty accounts for 14.6% of the error while the winds aloft uncertainty accounts for 6.5%. The uncertainties in dispersion track explain most of the remaining variance, 17.1%. The cruise speed and ambient temperature uncertainties together comprise less than 2% of the total variance.

7 ASSUMPTIONS

As with any model of this type, many necessary assumptions were made in the course of developing SAGE Version 1.5. Based on the time and resources available, these assumptions were reasonable in developing a model that can predict aircraft fuel burn/emissions at the level of error specified in the previous discussions. These assumptions will need to be reviewed and considered as candidates for improvement during development of future versions of SAGE.

The following list is an aggregation of the important assumptions made in developing SAGE Version 1.5. It should be noted that the various methods/components within the model also represent assumptions. These components are generally not listed since they represent the methods adopted into the model rather than actual assumptions. They are, however, referred to when appropriate.

- ISA atmospheric conditions (sea-level static) and standard lapse rates were used.
- Winds are not modeled.
- Relative humidity of 60%.
- Specific heat ratio of 1.4.
- Pressure altitude assumed.
- Straight line between trajectory data points assumed.
- Constant cruise altitudes and speeds assumed for use with generated trajectories.
- Vertical and horizontal trajectory dispersions used with OAG-based flights are dependent on trip distance.
- Special use airspaces are not modeled except those taken into account by ETMS flights.
- Average airport-specific taxi times were used.
- Aircraft matching/substitution tables were developed manually by referencing aircraft performance, size, and shape characteristics from various sources including industry and government sources.
- Takeoff weight is based on SAE AIR 1845 stage categories (trip distance).
- Fuel tankering is modeled by increasing takeoff weights by two corresponding stage lengths.
- No derated takeoff modeling assumed.
- No weight gain with time in service.
- Due to discretization in modeling, aircraft weight is assumed to remain constant for a flight chord (segment) but gets debited by the amount of fuel burn after each chord (i.e., after each step).
- The fuel burn during takeoff ground roll is small enough so that aircraft weight at liftoff is equal to that at the start of takeoff ground roll.
- Engine deterioration effects are not modeled.
- Fuel combustion assumed to be 100% with corresponding conversion of fuel into CO_2, H_2O, and SO_2.

- SO_2 is reported as SOx since all of the sulfur has been accounted for.
- 7% power setting assumed during taxiing and idle activities.
- Forecasting is based on a week's worth of scheduled flights used to obtain percent differences which are then applied to a baseline inventory.
- Replacement aircraft in forecasting is based on a pool of current state-of-the-art (best practices) aircraft developed from BACK Aviation's "on order" aircraft fleet.
- Average airport-specific visibility conditions used to model airport capacities.
- Airport capacities are assumed to stay constant during forecasting.
- No en route delays are modeled except those captured through ETMS radar trajectories.

8 CONCLUSIONS

This paper described the initial assessment of uncertainties in SAGE Version 1.5. The modular assessments which primarily focused on components associated with aircraft performance indicated overall good agreement with measured data. The L/D and SFC comparisons generally showed within 10% agreement although a few aircraft showed differences in the 20-25%. The fuel flow comparisons showed some noticeable scatter, but there did not seem to be any bias and the overall mean difference was under 7%. This appears to indicate proper aircraft performance modeling within SAGE.

A consistency check with INM takeoff and approach profiles showed good agreement. This was expected since the INM procedural framework is embedded within SAGE. Although some differences were shown for certain aircraft types when comparing takeoff and climbout distances, they were overall small.

The modular assessments also included a cursory evaluation of the SAGE forecasting methodology involving flight schedule growth. The comparisons of forecasted and historical schedules appear to show very good agreement to well under 5% difference for most of the days and weeks compared. Further assessments should include additional historical schedules as they become available and categorizations of flights by carrier, equipment type, and OD pairs.

The system-level aggregate fuel burn comparisons also showed very good agreement with measured data. For the comparisons against data from the major US carrier, the overall mean difference was less than 3% when ETMS and OAG flights are combined. ETMS flights appear to have produced better overall results than OAG flights which seem to under-predict on average. However, OAG flights produced a lower standard deviation of 10.7% as opposed to 13% for ETMS flights. Since these numbers are relatively similar, it is difficult to make conclusions other than it may be due to greater scatter in the ETMS radar data (e.g., erratic trajectories, speed data, etc.). Similar comparisons against data from two major Asian carriers showed an overall difference of 0.42%. These results indicate that at the system level, SAGE is very accurate on an overall basis, but can still be improved to reduce the scatter.

In addition to the comparisons to reported data, an error source assessment was conducted mainly through the use of Monte Carlo simulations. These assessments helped to identify the most significant sources of error contributing to the variance of fuel burn and emissions results. The analyses showed that the uncertainties in engine and aerodynamic performance have the largest impact on system errors, accounting for around 60-70% of total variance in full-mission fuel burn results. The uncertainties in winds aloft and take-off weight explain another 20-25%. Since the uncertainty in ambient temperature during cruise is relatively very small, its impact on full-mission fuel burn results is minimal.

Lastly, a listing of the major assumptions in developing the model was provided. This list includes further candidates for review and improvement in future versions of SAGE.

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