Frank Jelinek
Sandrine Carlier
James Smith

EUROCONTROL
Experimental Centre

Advanced Emission Model (AEM3) v1.5

Validation Report

EEC Report EEC/SEE/2004/004

EUROCONTROL

Advanced Emission Model (AEM3) v1.5

Validation Report

Frank Jelinek, Sandrine Carlier, James Smith

EEC Report EEC/SEE/2004/004

© European Organisation for the Safety of Air Navigation EUROCONTROL June 2004

This document is published by EUROCONTROL in the interest of the exchange of information. It may be copied in whole or in part providing that the copyright notice and disclaimer are included.
The information contained in this document may not be modified without prior written permission from EUROCONTROL.

EUROCONTROL makes no warranty, either implied or express, for the information contained in this document, neither does it assume any legal liability or responsibility for the accuracy, completeness or usefulness of this information

REPORT DOCUMENTATION PAGE

Reference: EEC / SEE / 2004 / 004	**Security Classification:** Unclassified
Originator: EEC / SEE / Society Environment Economy	**Originator (Corporate Author) Name/Location:** EUROCONTROL Experimental Centre Centre de Bois des Bordes B.P.15 91222 BRETIGNY SUR ORGE CEDEX France Telephone: +33 1 69 88 75 00
Sponsor: EATM Environment Domain	**Sponsor (Contract Authority) Name/Location:** EUROCONTROL Agency Rue de la Fusée, 96 B –1130 BRUXELLES Telephone: +32 2 729 90 11

TITLE:
The Advanced Emission Model (AEM3) - Validation Report

Authors :	**Date**	**Pages**	**Figures**	**Tables**	**Appendix**	**Reference**
Frank Jelinek (EEC), Sandrine Carlier, James Smith	31/12	79	21	40		

EATMP Task Specification	Project	Task No. Sponsor	Period
-	AEM3v1.5 - Validation	-	2002/2003

Distribution Statement:
(a) Controlled by: EUROCONTROL Project Manager
(b) Special Limitations: None
(c) Copy to NTIS: ~~YES~~ / NO

Descriptors (keywords):
Global Emissions - AEM - NOx - CO - HC - CO2 - H2O - SOx - Benefits - EEC - etc

Abstract:

This report documents the validation of the Advanced Emission Model (AEMIII) Version v 1.5. The Advanced Emission Model has been developed at the EUROCONTROL Experimental Centre and has been used in first studies to estimate aviation emissions and fuel burn. It is using ICAO Engine Exhaust Emissions Data bank (05/2003), the Eurocontrol Base of Aircraft Data (BADAv3.5) and an improved version (EEC-BM2) of the Boeing Method2 (BM2) trying to produce most reliable emission estimations for all phases of flight.

Table of Contents

REPORT DOCUMENTATION PAGE 2

REPORT DOCUMENTATION PAGE 3

TABLE OF CONTENTS 4

LIST OF FIGURES 7

LIST OF TABLES 7

LIST OF ABBREVIATIONS 9

EXECUTIVE SUMMARY 1

INTRODUCTION 3

OVERVIEW OF AEM3 5

Traffic Inputs 5

Fuel Burn Calculations 5

Emission Calculations 6

AEM3 User Options 8

Taxi Times 8

Completing Flight Profiles 8

Traffic sample entry time 9

The AEM3 4D Analysis Window 9

Multi-dimensional Gridded Output 9

VALIDATION APPROACH 11

What Should Be Verified and Validated ? 11

How Should This Be Done ? 11

MICROSCOPIC APPROACH 13

Importing 4D Flight Profiles 13

Flight Profile Completion 13

Fuel Burn and Emissions Calculations 13

Other Calculations **14**
Aircraft Database 14
Engine Databases 14
World Airport Database 14
Atmospheric Data 15
Fuel Burn Rates and Emissions Indices 15
Distance Calculations 15
Traffic Data Filters 15

MACROSCOPIC APPROACH: FUEL BURN VALIDATION **17**
General Approach **17**
Data Collection **17**
SITA Operational Flight Plan (OFP) Dataset 17
SITA Data Preparation 18
FDR Dataset 18
FDR Data Preparation 20
Data Preparation Summary 20
AEM3 User Options for Validation **20**
Traffic Sample Entry Time 20
Taxi Times 20
Geographic Area 21
Flight Profile Completion 21
Output data analysis and results – Flight time and Fuel burn estimation with AEM3 **22**
Analysis of LTO Cycles 22
Take Off Phase 23
Climb Out Phase 24
Approach Phase 25
Taxi Out Phase 26
Analysis of LTO Cycles: Summary 29
Flight Profile Analysis: Flight Duration 30
Flight Profile Analysis: Fuel Burn 32
SITA data 39
SITA Versus FDR Results 41
Flight Profile Analysis: Fuel Flow 42

MACROSCOPIC APPROACH: EMISSIONS VALIDATION 49
CO_2, H_2O, S_20 49
NO_x, CO, HC 49
ANCAT 49
NASA 49
NOx, CO and HC Distribution 50
NOx Average Emission Indices from ANCAT and NASA 54
Emissions Along the Flight Profiles 55
VOC / TOG 59

LIMITATIONS AND DEPENDENCIES 61
Limitations due to the tool conception 61
Limitations due to the underlying databases 62

CONCLUSION 63

REFERENCES 67

List of Figures

Figure 1: The AEM3 fuel burn vs. operational fuel burn for 3850 flights 1
Figure 2: The AEM3 fuel calculation cycle 6
Figure 3: AEM3 Profile Completion Options 8
Figure 4: Average Taxi Out duration – SITA data 27
Figure 5: Evolution of fuel flow for a 600 km mission 42
Figure 6: Evolution of fuel flow for a 3300 km mission 43
Figure 7: Evolution of fuel flow for a 6600 km mission 43
Figure 8: Fuel flow limits – A319 45
Figure 9: Fuel flow limits – A320 45
Figure 10: Fuel flow limits – A321 46
Figure 11: Fuel flow limits – A330 46
Figure 12: Fuel flow limits – A340 47
Figure 13: Emissions Comparison of 757-200 for a 750 km and 5500 km Mission [Ref 11] 50
Figure 14: Comparison of Emissions Produced by AEM3 with FDR data 51
Figure 15: Comparison of emissions produced by AEM3 with SITA data 53
Figure 16: Pollutant distribution per phase - AddAll 56
Figure 17: Pollutant distribution per phase - NoAdd 57
Figure 18: Evolution of NO_x, CO and HC emission indices along a 600 km mission . 58
Figure 19: Evolution of NO_x, CO and HC emission indices along a 3300 km mission 58
Figure 20: Evolution of NO_x, CO and HC emission indices along a 6600 km mission 59
Figure 21: The AEM3 fuel burn vs. operational fuel burn for 3850 flights 65

List of Tables

Table 1: Fuel burn and emission calculation through AEM3 7
Table 2: Coefficients for emissions calculation 7
Table 3: 2D Grid sample 10
Table 4: Aircraft Types in SITA Data Sample 17
Table 5: Aircraft Types for FDR Validation 19
Table 6: Number of FDR Movements 19
Table 7: Great circle distance between city pairs in FDR data set 19
Table 8: Duration and fuel ratio per LTO flight phase 22
Table 9: Take Off per aircraft type 23
Table 10:Climb Out per departure airport 24
Table 11:Climb Out per aircraft type 24
Table 12: Approach per departure airport 25
Table 13: Approach per aircraft type 25
Table 14: Taxi Out Per departure airport 26
Table 15: Duration ratio per aircraft type (FDR) 30
Table 16: Duration ratio per aircraft type and distance range (FDR) 31
Table 17: Duration ratio per aircraft type and take-off weight (FDR) 31
Table 18: Duration ratio per aircraft type (SITA) 32
Table 19: Duration ratio per distance range (SITA) 32
Table 20: Fuel ratio per ACType 33
Table 21: Fuel ratio per city pair 34

Table 22: Fuel per distance 35
Table 23: Maximum distance range at full load 35
Table 24: Weight categories for FDR data (kg) 36
Table 25: Traffic Sample Weight Limits 36
Table 26: Fuel ratio per Take Off Weight 37
Table 27: Fuel ratio per Take Off Weight and Distance Range 38
Table 28: Fuel ratio per ACType 39
Table 29: Fuel ratio per departure airport 40
Table 30: Fuel per distance 40
Table 31: FDR and SITA difference against AEM3 41
Table 32: Corrected fuel ratio per ACType 41
Table 33: Variation in published coefficients for fuel-proportional emissions (%) 49
Table 34: Emission distribution for FDR data 51
Table 35: Emission distribution per ACType for FDR data 52
Table 36: Emission distribution for SITA data 53
Table 37: Published average $EINO_x$ (g/kg fuel) of reference projects [Ref 12] 54
Table 38: AEM3 estimated $EINO_x$ averages in g/kg fuel with FDR data 55
Table 39: AEM3 estimated $EINO_x$ averages in g/kg fuel with SITA data 55
Table 40: Pollutant distribution per flight phase (%) 56

List of abbreviations

AEM Advanced Emission Model
AEM3 Advanced Emission Model, 3rd version
AMOC ATFM Modeling Capability
ANCAT Abatement of Nuisances Caused by Air Transport
ATC Air Traffic Control
ATM Air Traffic Management
BADA Base of Aircraft Data
BEN Benzene
BM2 The Boeing Method 2
EEC-BM2 The EUROCONTROL modified Boeing Method 2
CDRate Climb/Descent rate
CFMU Central Flow Management Unit
CO Carbon Monoxide
CO_2 Carbon Dioxide
Contrail Condensation trail
CORINAIR Co-oRdination of INformation on the Environment
DAC Dual annular combustor
DLR Deutsche Forschungsanstalt für Luft- und Raumfahrt e.V, Germany
EEC EUROCONTROL Experimental Center
EEC-BM2 EEC corrected BM2
EI Emission Index
EPA (U.S.) Environmental Protection Agency
FDR Flight Data Recordings
FL Flight Level
GIS Geographical Information System
H_2O Water
HC Hydrocarbon
ICAO International Civil Aviation Organisation
Lat Latitude
Long Longitude
LTO Landing- and Take-Off cycle
Max Maximum
Min Minimum
MS Microsoft
NASA National Aeronautics and Space Administration
NM Nautical Mile
NO_x Oxides of Nitrogen
OAG Official Airline Guide
PIANO Project Interactive Analysis and Optimisation program
RAMS EUROCONTROL Re-organised ATC Mathematical Simulator
RFL Requested Flight Level
SAC Single annular combustor
SEE Society, Environment, Economy
SO_x Oxides of Sulphur
TEA Toolset for Emission Analysis
TOG Total Organic Gases
TOW Take-Off Weight
VOC Volatile Organic Compounds

Executive Summary

The importance of global emission analysis tools in the support of the political decision making process is increasing with the increasing public interest in questions concerning the environmental impact of aviation.
Since decisions taken can have significant economical consequences on all aviation stakeholders, e.g. airlines, airports, air traffic service providers etc. it is crucial to assure that the information provided into the political decision making process is reliable.
This requires a serious verification and validation of all tools used in above context.
A keyfactor for such validation process is the availability of operational airline data holding precise flight profile and fuel burn information. Although the airlines would be the first to feel the potential consequences of changes in the aviation system motivated by environmental issues, such as fuel taxes, environmental route charges, emission landing fees etc., it has been extremely difficult to obtain operational data from airlines for the purpose of tool validation.
The situation for emissions is even more complex. Emission information for given aircraft - engine combinations is not available to the research community. Test bed information from the engine certification process is only available for ground level. The number of tests per engine is statistically not sufficient. The effect of the engine installation in the airframe and changes in terms of emission indices as a result of changing aircraft attitude, altitude, Mach number, weight etc. are not incorporated in this data available in the ICAO Engine Exhaust Emission Databank.
As a consequence, for tools used in the past, only rough error estimations have been possible. Error margins of 30% and more for fuel burn and emissions have been reported even in the context of European environmental reference projects such as ANCAT/EC1 & EC2, MeeT, etc.
The realism of the AEM3 results is extremly positive and goes beyond the expectations at start of the project.
The results are further visualised for all 3850 mission with FDR data sets available to this validation project in the figure below:

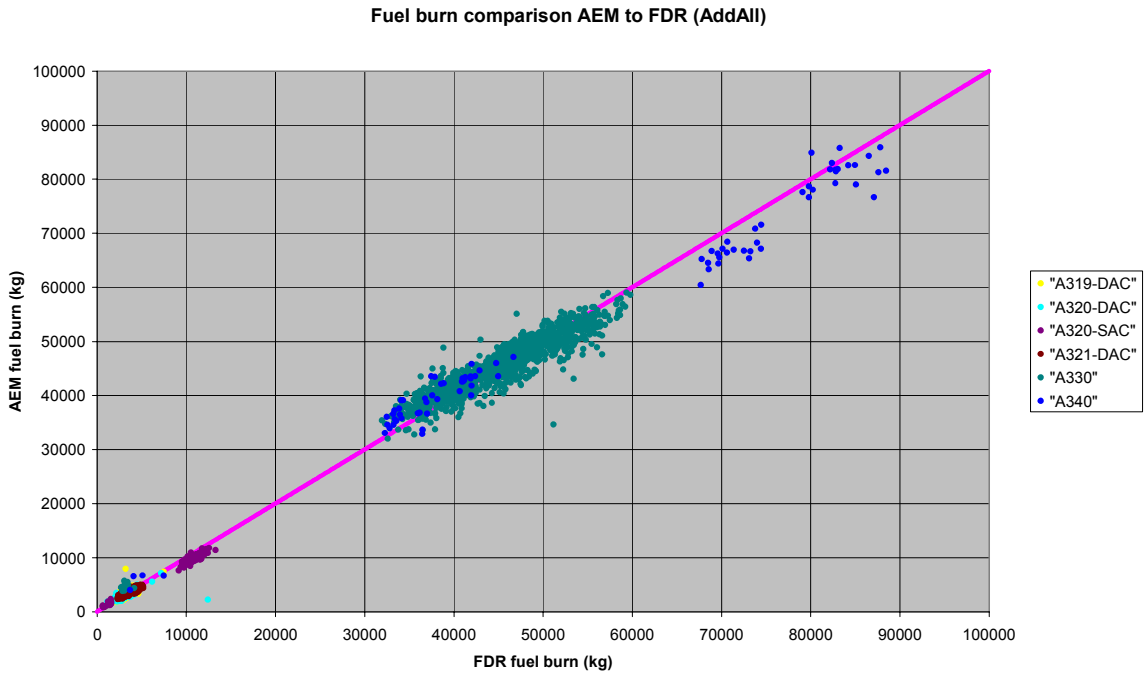


Figure 1: The AEM3 fuel burn vs. operational fuel burn for 3850 flights

Despite the known error margins for the LTO operations (of relative short duration), the overall fuel error for complete missions is only about +1 %. After deduction of the error on duration of +2 % due to flight completion, the remaining fuel error is an under estimation of -1 %.

This extremely positive result of AEM3 v1.5, goes as well significantly below the acceptance limits as defined by ICAO/CAEP6.IP5 for the difference between measured and calculated fuel flow and directly proportional emissions to be within ±10%.

The validation of AEM3 highlights significant differences for high and as well low thrust fuel flows compared to fuel flows documented in the ICAO Engine Exhaust Emissions Databank. This is a fundamental issue which requires further discussions with domain experts, since this leads to systematicly wrong fuel burn and emission estimations for any project relying on the ICAO fuel flows.
The distribution of NO_x, CO and HC correspond to ranges published by NASA, if low fuel flow emission inidicies are limited to the 7% EIs documented in the ICAO Exhaust Engine Emissions Databank. At the same time NO_x average emission indices is about 13.5 g/gk fuel, which is very close to the published ANCAT findings.
If the emission indicies for very low fuel flows are not limited to the 7% limits, but extrapolated below this limit, significantly higher CO and HC emissions are estimated by AEM3 for a typical mission. Also this is one of the unexpected results of the AEM3 validation exercise it is considered that results obtained in this way are more realistic. Although the problem is known by ICAO/CAEP/6-IP5, guidance material is not yet available.
As a result of this validation exercise it can be concluded that the fundamental approach implemented within AEM3 v1.5 is leading to results with a very high level of realism. Fuel burn calculations, based on BADA fuel flows are very close to real life quantities. Consequently, the same can be concluded for the fuel burn proportional pollutants, e.g. H_20, SO_x and CO_2. NOx results align with estimations of earlier domain expert projects and are based on a variation of the the widely recognised and accepted BM2 method, BM2-EEC modified.
Additional validation against FDR data from more airlines covering additional aircraft types is envisaged, where this depends mainly on the airlines readiness to support such validation activity with operational data.

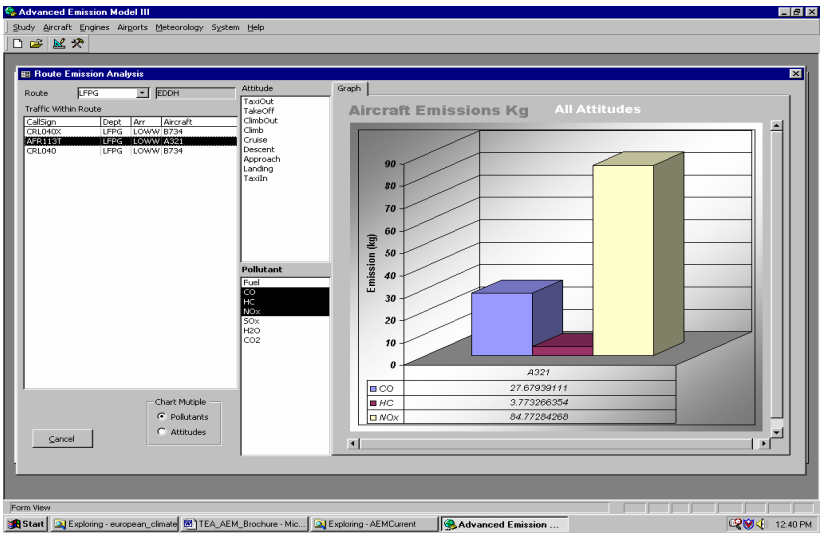
Introduction

During recent years, AEM3 has been used at an international level within the ICAO/CAEP process to perform global emission studies and within EUROCONTROL, to study the environmental benefits of the Free Route Airspace Project (FRAP), the Mediterranean Free Flight (MFF) Programme and the advantages of the European wide implementation of the Reduced Vertical Separation Minima (RVSM) Flight Level System.
During 2004 AEM3 v1.5 will be used to re-examine MFF based on larger Fast-Time Simulation traffic samples, study the environmental benefit of Continous Descent Approaches in Support of SOURDINEII, and analyze the potential environmental benefit of AMAN, CEATS and DyMEAN implementations.
A distribution of AEM3 v1.5 to a wider group of users is planned for 2004. This has motivated the current validation project on AEM3 version 1.5.
Six Global emission studies using AEM are scheduled for 2005.
Further, AEM3 will be integrated into PAGODA-PRISME - the EUROCONTROL Dataware house - to support European Commission on aviation fuel burn and emission reporting requirement in the context of EMEP etc.
These plans for use and distribution of AEM3 v1.5 gave the motivation for this validation project.

The present validation report aims to document the validation of AEM3 in its version 1.5.

After providing a general overview of the model, the report is structured in the following way:
The section entitled “Microscopic Approach”, provides an explanation as to how AEM3 code is verified and what are the key points which have been tested.
In a second part, (Macroscopic Approach - Fuelburn validation), AEM3 is considered as a black box. Its results are compared against real operational data from two airlines. The focus is first put on the LTO, detailing each phase of the LTO cycle. In a second time, flight profiles are considered in their whole. After looking at the duration error, fuel burn and then fuel flow all along flight profiles are considered.
In a third section, the calculated emissions are compared against results of earlier domain reference projects.

The Advanced Emission Model (AEM3) is a stand-alone system used to estimate aviation emissions (CO_2, H_2O, SO_x, NO_x, HC, CO, Benzene, VOC, TOG) and fuel burn. It is able to analyse flight profile data, on a flight-by-flight base, for air traffic scenarios of almost any scope (from local studies around airports to global emissions from air traffic). The system runs stand-alone on any standard office PC, where such PC, at a minimum, should be equiped with MS-Windows2000 and Office2000. It is primarily based on MS-ACCESS2000.



AEM3 uses several under-lying system databases (aircraft, aircraft engines, fuel burn rates and emission indices) provided by several external data sources. All of those data sources are well recognised and accepted in not only the emission modeling context and assure each for themselve data accuracy and validation tests. This assures the quality of the information used by AEM3. This system information is combined with dynamic input data, represented by the air traffic flight profiles.

Traffic Inputs

AEM3 imports any traffic data which has to be provided to the system in form of two input files using the AEM3 input format. Those flight information in those two files is linked by the flight call sign.

Traffic.txt contains general flight and schedule information including callsign, departure time, departure and arrival airports, and the aircraft type. For example:
040800 BAW138 VABB RWY EGLL RWY B742 Commercial DefaultACNavEquip 340 340 340
040908 FIN907 EFHK RWY LEBL RWY MD80 Commercial DefaultACNavEquip 320 320 330

Flight.txt provides information about the flight profile. For each point, AEM3 imports the callsign, flight attitude, ground speed, climb/descent rate, and the 4D point coordinate (time, latitude, longitude, and altitude). A sample record is shown below:
KEY;AZA465;05:49:18;Cruise;HEIDL;Navaid;FALSE;FALSE;445.00;0.00;49.350318;8.483338;350.00;350.00;350.00;FlightPhaseEnroute;350.00;60.00;

Fuel Burn Calculations

Below 3000 ft, the fuel burn calculation is based on the Landing and Take-Off Cycle (LTO) defined by the ICAO Engine Certification specifications. ICAO LTO covers four engine operation modes which are used to model Taxi-Out, Take-Off, Climb-Out, Approach, Landing and Taxi-In aircraft operations. The *ICAO Engine Exhaust Emissions Data Bank*

0 includes emission indices and fuel flow for a very large number of aircraft engines. AEM3 links each aircraft appearing in the input traffic sample to one of the engines in the *ICAO Engine Exhaust Emissions Data Bank*.
Above 3000 ft, the fuel burn calculation is based on the “Base of Aircraft Data“ (BADA). This database provides altitude and attitude dependent performance and fuel burn data for more than 150 aircraft types, and the most recent version (3.5) includes nearly 90 % of the aircraft types operating in European airspace. The BADA is developed and maintained by the EUROCONTROL Experimental Centre.
The following figure presents a simplified view of the different approaches followed by AEM3 to obtain most realistic fuel burn estimations for all phases of the flight profile.

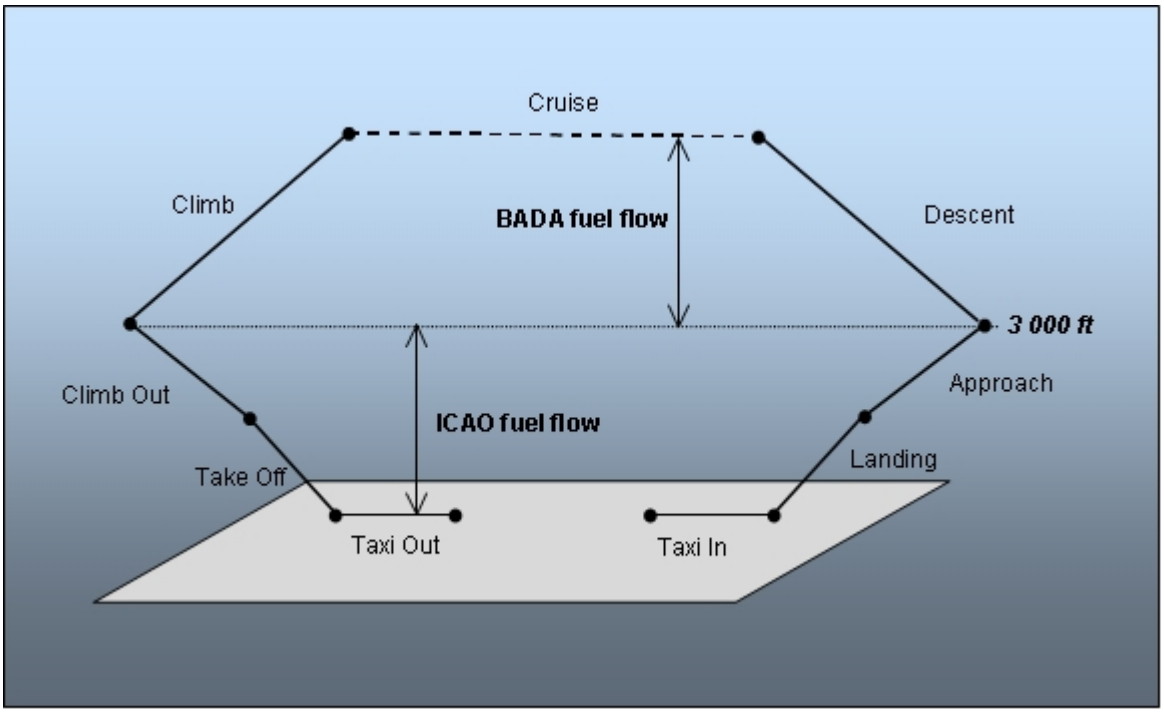


Figure 2: The AEM3 fuel calculation cycle

The LTO cycle can be added to all input flight profiles, even than when data for those operations is available. The application of the ICAO LTO cycle is common practice in aviation emission estimation and assures complete information for all profiles during those phases of flight. Nevertheless, AEM3 offers the user the option to perform the calculation only on the initial portion of each flight (i.e. without completing the missing portions of the flights). In this case, BADA is used to estimate fuel burn for the entire flight profile, including low flight levels.

Emission Calculations

Below 3000 ft, the emission calculation is based on the *ICAO Engine Exhaust Emissions Data Bank*.
Above 3000 ft, the emission calculation also based on the *ICAO Engine Exhaust Emissions Data Bank*, but emission factors and fuel flow is adapted to altitude using a method developed by The Boeing Company (The Boeing Method 2 is described in Annex A). The "Boeing Method 2 – EUROCONTROL modified" uses an improved formula for the humidity correction factor to give more accurate results. The differences in results between the two methods, however, is negligible within the methodology as a whole.

In this way, emissions for the pollutants NO_x, HC, CO can be estimated. The emissions for the pollutants H_2O and CO_2 are direct results of the oxidation process of carbon and the hydrogen contained in the fuel with the oxygen contained in the atmosphere. The SO_2 emissions depend on the sulphur content of the fuel used. All three depend directly proportionally from the fuel burn.

Volatile Organic Compounds (VOC) and Total Organic Gases (TOG) results are proportional to the HC emissions and are estimated by using a method published by the U.S. Environmental Protection Agency (EPA).

The following table summarizes the underlying approach within AEM3 used to estimate fuel burn and emissions.

	Fuel burn	**NO_x, HC, CO**	**CO_2, H_2O, SO_x**	**VOC, TOG**
Below 3000 ft LTO flight phases	ICAO Engine Exhaust Emissions Data Bank		Proportional to fuel burn	Proportional to HC emissions (EPA method)
Above 3000 ft Non-LTO phases	BADA data	Boeing Method 2		

Table 1: Fuel burn and emission calculation through AEM3

An understanding of fuel composition is vital for determining the proportional coefficients between fuel burn and emissions. The constants used in AEM3 for this validation are presented below. These are average values obtained from an intensive literature review.

Pollutant	**Coefficient**
CO2	3.149 kg / kg Fuel
H2O	1.230 kg / kg Fuel
SO2	0.00084 kg / kg Fuel
VOC = HC × 1.0947 VOC/HC correction factor	
acetaldehyde	VOC × 0.0519 acetaldehyde / VOC correction factor
Acrolein	VOC × 0.0253 acrolein / VOC correction factor
POM as16-PAH	VOC × 1.166E-4 16-PAH / VOC correction factor
POM as 7-PAH	VOC × 1.049E-6 7-PAH / VOC correction factor
Styrene	VOC × 0.0044 styrene / VOC correction factor
TOG = VOC × 1.1167 TOG/VOC conversion factor	
1,3-butatdiene	TOG × 0.0180 1,3-butatdiene fraction
benzene	TOG × 0.0194 benzene fraction
ethylbenzene	TOG × 0.0017 ethylbenzene fraction
formaldehyde	TOG × 0.1501 formaldehyde fraction
propionaldehyde	TOG × 0.0095 propionaldehyde fraction
toluene	TOG × 0.0052 toluene fraction
xylene	TOG × 0.0048 xylene fraction

Table 2: Coefficients for emissions calculation

AEM3 User Options

AEM3 provides many user-selectable options which allow to influence the treatment of the data and thus may affect the results.

Taxi Times

AEM3 includes a database for taxi times for about 3000 airports. The database is based on two main sources: operational airline information extracted out of SITA messages (taxi out) and airport declared taxi times. AEM3 adds virtual taxi legs using taxi in and out times from its taxi time data base. AEM3 first tries to use the operational airline taxi time information. If this data is not available for the airport in question, AEM3 looks in the table for airport declared taxi times. Where in either tables taxi time information for the specific airport is available, a system default taxi time is used by AEM3. Where the users does not which AEM3 to apply this “cascading” approach, only airport declared times can be used or the default taxi time is applied to all flights of the user’s study.

Completing Flight Profiles

In many cases, the flight profile information available to studies is incomplete. For example, the flight profile points may begin some time after departure and/or end before arrival. In such cases, the user may choose to complete the partial profiles.
If flight profile completion is not requested by the user, only the points from the original input files are used for the fuel burn and emissions estimations. All data, including any points below FL30 (LTO cycle), is kept and used for the calculation. Fuel burn is estimated with BADA data and emissions with the Boeing Method 2 methodology (Annex A).
If profile completion is required, two user options are available: "complete all operations" and "complete LTO only". In both options, all data under FL30 is deleted and replaced by the standard ICAO LTO cycle. Consequently, AEM3 fuel burn and emissions results for LTO become a function of aircraft-engine combinations and no longer dependent upon the individual flight’s arrival or departure profile at a given airport (since the LTO cycle will be identical for all flights). If the "complete all operations" is requested, AEM3 will close any additional gap in the flight profile (beyond the LTO cycle) using a linear interpolation between the known profile points. This allows a “best-practice estimation” of flight profile data in cases where the available data is incomplete – thus AEM3 allows fuel burn and emissions estimations even for very low fidelity traffic datasets.

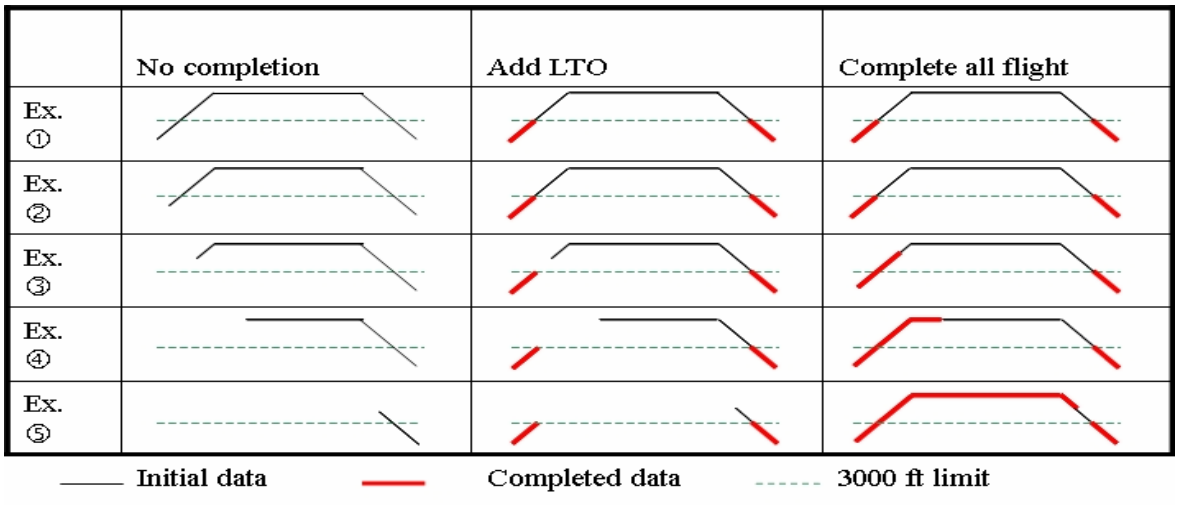


Figure 3: AEM3 Profile Completion Options

Traffic sample entry time

Normally, emissions estimations should begin at the flight's off-block time. Sometimes known as pushback time, this is the moment when an aircraft departs from its gate. This time stamp is not available for all traffic scenarios; in some cases the Start-of-take-off time is provided and sometimes the profile data begins at some altitude above the ground. AEM3 provides a user option specifying whether the first profile point should be interpreted by the system as off-block, take-off or first leg in the sky.
When the traffic.txt input file holds departure times (off-block or take-off), the corresponding option should be selected. When neither of these times is available in the traffic.txt input file (typically when the entry time in the traffic sample is the time of the first data point in the flight file), the option to use is "first leg start".
If off-block or take-off option is selected and profile completion is required, AEM3 will use the entry time, the time stamp appearing in the traffic file, to complete the flight profile. If neither of these is known, the "first leg start" time is used and AEM3 estimates the departure time by completing the flight profile from this first point (at altitude) in a linear way back to the ground. Obviously the use of the "first leg start" option introduces an additional error, since such artificially straight profiles do not mimic the operations of aircraft following SIDs and STARs etc.

The AEM3 4D Analysis Window

AEM3 automatically uses the most widely separated geographical coordinates and most extreme time stamps (minimum and maximum longitude, latitude, altitude, and time) found in the input traffic sample to define the 4D analysis window. This window defines the boundaries inside which the aircraft operations fuel burn and emissions are calculated. Of course, in addition to this automatic analysis area definition, AEM3 allows the user to manually override the analysis window boundaries and time limits.
To overcome the potential limitations of such a rectangular analysis window, a further user option has been provided within AEM3 which allows the user to "cut" the AEM3 output data into a geographical area defined by an irregular polygon.
If the user adds LTO cycle times to the initial flight profiles, the entire LTO operations are considered by AEM3 to geographically take place at the airport coordinates. As a consequence, all LTO operations are considered to be either inside or outside the geographical zone, depending upon whether the airport coordinates are inside or outside the analysis window. This can result in an error in the emission estimations for those flights which use airports just inside or outside the AEM3 analysis window.

Multi-dimensional Gridded Output

When the fuel burn and emissions computations are complete, AEM3 provides an option to produce 2-, 3- or 4-dimensional gridded output. Grid dimensions and time steps for this feature are user definable. The grids are produced as follows:
2D Grid: fuel burn and emissions data in 2D grids based on lat and long
3D Grid: fuel burn and emissions data in 3D grids based on lat, long and flight level
4D Grid: fuel burn and emissions data in 4D grids based on lat, long, flight level and time

A sample set of records of a 2D Grid is shown below:

Lon	Lat	Distance	Fuel	CO	HC	SOx	NOx	CO2	H2O
-71	42.5	27	573.20	1.72	0.09	0.48	6.29	1805.02	705.04
-70.5	42.5	43	637.17	4.67	0.37	0.54	13.69	2006.44	783.72

-70	42.5	33	473.50	1.57	0.11	0.40	9.22	1491.05	582.40
-70	43	57	302.68	4.74	0.38	0.25	5.21	953.15	372.30
-70	43.5	48	256.08	3.58	0.28	0.22	3.66	806.40	314.98
-69.5	43.5	11	17.11	0.99	0.08	0.01	0.16	53.87	21.04
-69.5	44	59	79.59	5.25	0.43	0.07	0.75	250.64	97.90
-69.5	44.5	53	61.97	4.60	0.37	0.05	0.60	195.15	76.22
-69	44.5	6	6.98	0.52	0.04	0.01	0.07	21.99	8.59
-69	45	59	67.31	5.30	0.43	0.06	0.65	211.96	82.79
-69	45.5	54	60.69	4.97	0.40	0.05	0.59	191.10	74.64

Table 3: 2D Grid sample

Distance, fuel and emissions are gridded. VOC/TOG are not currently gridded directly by AEM3, since those pollutants seem to be mainly of concern in the context of Local Air Quality studies and less in the context of global emission studies. Nevertheless, where a user requires this information VOC/TOG grids can be easily produced based on the HC grid, since VOC/TOG are proportional to HC.
Obviously the gridding feature of AEM3 requires dependent on the chosen grid granularity and dimension corresponding hardware performance of the used PC.

What Should Be Verified and Validated ?

The main focus for the validation was placed upon the following elements:
Flight profiles from different sources (F/T and R/T simulators, Radar, Flight planning) are accepted
User options are taken into account
Data inside AEM3 is up to date and consistent
Data is used at the right moment and context
Flight profile completion is performed correctly
Fuel burn and emissions calculations are correct
Calculations are performed within the correct geographical area
Supplementary calculations (eg. great circle distances) are correct
Fuel burn and emissions estimation results are stable and compare well against real data

Many of these items are not discussed in detail in this report, since they consist of software code inspection and verification and are highly specific to each item. However the testing procedure as well as items 3 and 6 are discussed in the section "Microscopic Approach". Focus is put on items 9 in "Macroscopic Approach: Fuel Burn Validation" and "Macroscopic Approach: Emissions Validation" sections.

How Should This Be Done ?

The verifcation and validation of these elements was conducted in two steps.
The first step was to ensure that AEM3 computes correctly and as designed. This was verified through a microscopic approach, which consists in a very effort intensive manual verification, step by step, of the different calculations performed by AEM3. The goal of this verification was to verify that the functional approach of AEM3 had been correctly implemented in its software code.
The second step followed a macroscopic approach. AEM3 was treated as a black box and its results were compared against in-flight airline data from flight data recordings.
Those two approaches are described in detail in the remainder of this document.

Before looking at AEM3 outputs, it was necessary to ensure that all AEM3 calculations are correct. The purpose of this step was to verify that the calculations inside the model perform as expected for the different options available. To meet this goal, a set of systematic tests was developed and each feature in AEM3 was verified. Particular attention was placed on the import and completion of the flight profiles and on the fuel burn and emissions calculations, as described below.
Each identified bug has been fixed and all the process of systematic tests reran, until all the calculations inside the model could be considered as correct.

Importing 4D Flight Profiles

The AEM3 analysis can be based on flight profile data from any source. Typical flight profile sources for emissions studies are simulator data (Fast-Time/Real-Time), flight plan data (CFMU, airlines etc,) or radar data (ATS providers).
As described above, AEM3 needs two input files. The traffic file includes call sign, entry time, departure and arrival airports, and aircraft type. The flight file provides the 4D flight profile points along with attitude, ground speed, and climb/descent rate at each point. These files need to be formatted into "AEM3 input format", as explained in section "Traffic Inputs". Reformatted data from many sources has been successfully tested in AEM3.
As for any other analysis tool, the quality of the output of AEM3 depends strongly on the quality and granularity of the traffic input data, since AEM3 is neither a simulator nor has it been designed to artificially create whole flights or significant portions of flights. Despite the fact that AEM3 verifies many criteria in the input data, it cannot correct all potential errors or inconsistencies in the input data and must rely upon the user to carefully verify the traffic input data.

Flight Profile Completion

Although AEM3 does not include a full flight profile calculator, profile points may be created using a linear interpolation between available profile points and departure / arrival airport (depending on user-selected options and the available input profile points). The correct implementation of this feature as a user selectable option has been tested. However the option has to be used with care, since it would allow, for example, a take-off at 1:00PM with the cruise phase beginning at 1:02PM at high altitude, even if such part of a flight profile would not be realistic. Consequently fuel burn and emission estimations produced for such artifical flight profile part would compare badly to operational figures.
Depending on selected user options and input data characteristics, AEM3 calculations are different (cf. section "AEM3 User Options") and results can differ. For example, if a profile completion is required and no off block or take off time provided in the input data source, AEM3 reconstitutes the flight profile "backwards" to the departure airport location to estimate a take off time. On the opposite if a profile completion is required and a take off or off block time is provided, AEM3 estimates the flight profile directly between the known take off time and the first available flight point at altitude.

Fuel Burn and Emissions Calculations

After fuel flow and emission indices for a given aircraft-engine combination (as a function of altitude and attitude) are extracted from the corresponding AEM3 system data tables, the calculations are performed along the individual profile on a leg by leg basis. The overall fuel burn and emissions for each leg are computed using the above factors as multipliers over the time duration of a leg.
AEM3 decomposes longer climb and descent legs to the same level of granularity (in altitude layers) as the fuel burn data provided by BADA, to ensure that the altitude dependency of fuel burn during climb and descent is considered in the most possible realistic way. The more flight points provided in the input data, the more legs available to

decompose the flight during the calculation; thus the more precise the fuel burn and emissions estimates will be.
To assure that this is done correctly within AEM3, the calculations were performed manually and compared to the AEM3 results.
As the Boeing Method 2 (Annex A) calculations are quite complex and thus difficult to reproduce manually on a leg by leg basis over full flight profiles, an independent verification tool was implemented using MS Excel. During the implementation of this verification tool, certain minor errors and some imprecision were found in the way Boeing Method 2 was coded in AEM3. While these problems were significant, it was felt that AEM3 had to be corrected before going of with validation. After the correction was made, AEM3 results did correspond to the verification tool expectations.

Other Calculations

AEM3 uses data from several external data sources. Emphasis on the choice for those data sources has been put on the aspect of their acceptance level. Most of those data sources can be chategorised as international domain reference or even standard.

Aircraft Database

The AEM3 aircraft database was initially based on the direct and equivalent modelling of aircraft as provided within BADA. Further equivalents have been added during 2002 and 2003 based on the experience gained from several emission studies using voluminous European and U.S. air traffic scenarios.
Tests during this validation exercise on the current aircraft database provided with AEM3v1.5 show that its aircraft database now includes aircraft representing more than 99.7 % of all flights over Europe. These tests were based on full European traffic days for the period between 1st March and 1st June 2003 with more than 2.000.000 flights. (see Annex C).

Engine Databases

The engine information matched to each aircraft is the key both for fuel burn information and emission indices.
Fuel burn rates for aircraft engine pairs are provided by BADA for aircraft operations above 3000ft. Below fuel burn rates per aircraft engine are extracted out of the *ICAO Engine Exhaust Emission Databank*, May 2003 (http://www.quinetiq.com/aircraft_emissions_databank). This database provides as well the and emission indices as a funcion of the aircraft engine type.
To create a homogeneous system throughout AEM3, aircraft/engine pairs are identified using the BADA database. In cases where the BADA files do not provide the engine type, the JPFleets database [Ref 16] is used to determine the aircraft/engine pair. The use of the engine database within AEM3 was validated during development and on an ongoing basis.

World Airport Database

This database provides the ICAO and IATA airport codes, latitude, longitude, elevation. Initially based on the AERO2K [Ref 20] airport database, AEM3 database has been updated using the last known and most complete information over the last years.
Based on the full European traffic year 2002, approximately 8,380,000 flights took off or landed from 2,861 different airports. Forty-seven of these airports are not identified by AEM3, with only 2 of them having more than 300 flights in 2002. Unidentified airports in AEM3 represent only 0.11 % of one year of European traffic.

Atmospheric Data

By default, AEM3 uses an atmospheric table of data defined as the International Standard Atmosphere and the U.S. Standard Atmosphere Supplements (for humidity) at 500 meter height intervals.
These values can be overridden by the user to model different weather situations. However, the current version of AEM3, when used in a standalone mode, requires that the same atmospheric situation is applied over the entire geographical area and time period under analysis. This limitation is avoided when AEM3 is used as a component of TEA (Toolset for Emission Analysis). In this configuration, time- and location- dependent weather data is provided to AEM3 by a more complex meteorological model (MM5).
Refer to appendices A and B of this report (separate document) for more information on sensitivity of AEM3 to atmospheric parameters.

Fuel Burn Rates and Emissions Indices

AEM3 has been updated with the most recent version of the ICAO engine exhaust emissions data bank (May 2003) and this will be updated with each new main release of ICAO engine exhaust emissions data bank.
The data available in the ICAO engine exhaust emission data bank is based on certification tests. Defined framework and procedures for those certification test assure the reliability of this data source.
The data provided within BADA is traceable since based on airframe and engine manufacturer propriatary information. BADA has accuracy information for each of its models. A BADA accuracy report is planned to be published during second half of 2004.
The AEM3 user may update the BADA data within AEM3 model as desired. Access to BADA requires a license agreement with EUROCONTROL.

Distance Calculations

AEM3 computes the total distance flown and the distance per flight phase for each flight. These distances are calculated using the great circle distance formula for each flight leg.
When LTO is added, LTO points are considered to occur at the airport lat/long. Consequently, the distances for taxiing, take off, climb out, approach and landing are equal to zero. Fuel burn and emission calculations for those modes is purely based on the time in such modes.
After verifying that the distance equitations are correctly implemented, AEM3 distances were compared to distances returned by the ArcView Geographical Information System (GIS) and a number of internet tools such as www.ar-group.com or http://www.notre-planete.info/geographie/distances.php. These comparisons confirmed the accuracy of distance calculations within AEM3.

Traffic Data Filters

AEM3 allows the user to filter the input traffic data based on a time period or geographic zone. As described above, the user can modify the default 4D analysis window which is defined by the minimum and maximum time, lat/long and flight level coordinates found in the input traffic data. The user may also provide the coordinates of an irregular polygon to filter the traffic in a more precise area. Refer to [Ref 19] for more details.
For each leg in the input flight file, a "fraction" representing the percentage of the leg inside the analysis window is applied to the fuel burn and emissions results for the leg. A substantial number of tests were performed, with varying analysis window configurations, using the ArcView GIS to verify that AEM3 applies this fraction correctly.

Macroscopic Approach: Fuel Burn Validation

The microscopic validation described in the previous section verified that AEM3 correctly performs its calculations as required. The goal of the macroscopic approach is to validate AEM3 results against operational airline figures (FDR data). For this purpose, AEM3 was treated as a black box.

General Approach

Different data sets from European airlines were available at the EEC, but most do not contain sufficient flight data for this validation. As a consequence, this validation exercise focused on two data sources: operational flight data recordings (FDR data) and operational airline flight plan information in form of SITA messages (SITA data).
SITA data provide the detailed planned route for the aircraft and the total quantity of fuel tanked. Since such fuel loading is based on airline statistics and aircraft-specific information, it presents a first baseline for comparison of results estimated by AEM3. FDR data provides fuel burn for each flight leg. FDR data allows detailed comparison along the flight profile and for each flight phase.

Data Collection

SITA Operational Flight Plan (OFP) Dataset

SITA OFP data, although flight plan data, are highly realistic since they are used for mission preparation. They are based on aircraft operating information from the aircraft manufacturer and statistical analysis by the airline of equivalent missions for the same city pairs and aircraft type. In some cases this information is available, in fact, for the same aircraft and/or engine.
SITA data for severn different traffic days was available. Each traffic day holds 500 to 800 flights. The total number of movements is 5170.
The flight profiles provided by SITA are not very detailed: in most cases, fewer than 10 points for each flight profile are available. Moreover, not all the information required by AEM3 is provided, as described below. For that reason, validation results based on SITA data have to be considered as a rough indication of validity only. The SITA dataset used in this effort provided some preliminary conclusions concerning AEM3 estimations for Boeing, McDonald-Douglas and certain Airbus aircraft.
The following table indicates the number of flights available from the SITA data for each aircraft type.

ACType	Number of flights
A306 (A300-600)	244
A310	255
A319	547
A320	973
A321	661
A340	95
B733 (B737-300)	1283
B735 (B737-500)	959
B742 (B747-200)	45
B744 (B747-400)	107
MD11	1
Total	*5170*

Table 4: Aircraft Types in SITA Data Sample

SITA Data Preparation

3790 out of the 5170 SITA OFPs were usable for the validation after preparation.
The conversion of the SITA data to AEM3 was not a direct nor straightforward operation. The primary problems encountered were the following:
The position lat/long was not provided. Only the name of the waypoints were available. The correspondence between point names and lat/long was performed using two different sources: AMOC data and waypoints from NIMA[1] file 0. A comparison of those two sources revealed significant differences between the two files for more than 100 point names. The correct lat/long value had to be estimated point by point using the aircraft ground speed and great circle distance. Moreover the position of "top of climb" and "top of descent" was not normally provided and had to be estimated.
Climb/Descent Rates were not provided. These were calculated using time and FL at each point. The results obtained have been compared to BADA Climb/Descent Rates and corrected if not realistic.
FL was provided only for cruise phases, not for climb and descent; thus the FL had to be estimated with BADA Climb/Descent Rates. When both the FL and Climb/Descent Rates were both missing, the values were estimated with a "typical BADA flight profile" determined for each aircraft with BADA data.
SITA contains errors, especially on flight level. For example FLs > 1000 have been found yet even the Concorde don't fly higher than FL 610. Most of these errors were corrected.
As a result, SITA data converted to AEM3 should be considered only as an approximation of the true or historical flight plan and therefore use of these profiles imposed a certain level of error in the results.

FDR Dataset

FDR data are operational flight data recordings acquired from a European airline. FDR provides detailed information for each flight point with good precision all along the flight profile. Detailed information is also provided for a certain number of significant flight profile positions such as 'Start of Taxi out', 'Start of Take Off', 35ft, 400ft, 1000ft, 1500ft, 2000ft, 3000ft and Touchdown for each flight, even when only a portion of the flight has been recorded (i.e., transatlantic flights often have incomplete profiles in FDR data). .
Unfortunately, in the data available to this validation project of AEM3, too little data was available after approach phase to allow a correct validation of the LTO In cycle.

Aircraft Types

FDR data cover 5 different aircraft types which are shown in the following table.

[1] This product was developed using DAFIF®, a product of the National Imagery and Mapping Agency. This product has not been endorsed or otherwise approved by the National Imagery and Mapping Agency, or the United States Department of Defense (10 U.S.C. 425).

ACType	BADA	Name in this report	AEM3 Engine	No. of Engines	Real engine
A319-112 CFM DAC	A319	A319-DAC	V2522-A5	2 CFMI	CFM56-5B5/2P
A320-214 CFM DAC	A320	A320-DAC	CFM56-5-A1	2 CFMI	CFM56-5B4/2P
A320-214 SAC	A320	A320-SAC	CFM56-5-A1	2 CFMI	CFM56B4/P
A321-111 CFM DAC	A321	A321-DAC	CFM56-5B1	2 CFMI	CFM56-5B1/2P
A330-223 PW	A332	A330	Trent 772	2 PW	PW4168A
A340-313	A343	A340	CFM56-5C2	4 CFMI	CFM56-5C4/P

Table 5: Aircraft Types for FDR Validation

Note: When the precise engine type installed on the aircraft appearing in the FDR and SITA data were not known, the engine type was determined using JPFleets database 0. In this database, 58 of the Airbus A330-223 corresponded to ICAO code A332 and 11 to ICAO code A333. All aircraft of the A330 fleet appearing in the provided FDR data are indicated as A332.
The following table indicates the number of movements available in each aircraft type, both initially and after data preparation .

ACType	Initial number of flights	Number of remaining flights for validation
A319-DAC	922	921
A320-DAC	911	911
A320-SAC	134	133
A321-DAC	475	475
A330	1661	1322
A340	238	87
Total	*4341*	*3849*

Table 6: Number of FDR Movements

The following table indicates the great circle distance for each city pair. (Each letter corresponds to an airport.) This distance is used in the validation to estimate distance range of the flights.

City pair	Distance km	Distance nm
B / C	106	57
K / J	230	124
K / H	478	258
K / I	605	327
K / A	856	462
K / C	3109	1679
K / B	3143	1697
K / D	6006	3243
K / F	6356	3432
K / L	6544	3533
K / E	6669	3601
K / G	7126	3848

Table 7: Great circle distance between city pairs in FDR data set

FDR Data Preparation

FDR data were of good quality. The conversion to AEM3 format was quite easy despite the appearance of a few problems:
Flight levels are in some FDR data set indicated as negative figures. Flights presenting negative FL were been deleted .
Flights taking off at a given day and landing in terms of date one day later.
Since AEM3 does not provide the notion of days or dates, such differences have to be expressed by translating day and time information in a virtual simulation time information, e.g. day one is expressed by simulation time 0 to 24, day two from 24 – 48 hours and so on.
Where AEM3 study samples include such cases any time information along all flight profiles of all flights has to be translated from real date and time to AEM3 simulation time.

Data Preparation Summary

Due to the rough granularity of the SITA OFP data, emphasis was placed on the FDR data source for this validation. SITA data was used to produce initial indications of the quality of the fuel burn and emissions estimation for aircraft types with no available FDR data. In addition, BADA model validation reports have been referenced and results are documented in this report.
In fewer than 10 cases, errors or discrepancies were found in the data (for example, duplicate call signs) and these flights were deleted.
Aircraft types for which AEM3 fuel burn and emission estimation have been verified in this validation project represent a coverage in terms of European movements of more than 40%. This figure is based on the verification of 8,379,134 movements above Europe in 2002 (source: CFMU for 2002), of which 3,416,018 flights are performed by aircraft types dealt with in this validation exercise.

AEM3 User Options for Validation

Concerning the completion of flight profiles, FDR flight profiles correspond to examples ②, ③ or ④ of Figure 3, although in some cases data for LTO phases was available. SITA data corresponds to example ①.

Traffic Sample Entry Time

FDR files provide a take-off and off block time but a manual check indicates that this value is not always correct. As a consequence, AEM3 had to be run with "first leg start" option, starting the analysis at the first “airborne” flight profile point available.
Although take-off and off block times are listed systematically in the available SITA OFP data, inconsistencies in these values were discovered (take-off and off block times are sometimes inverted in the files.) Since this was not systematically the case for all SITA data sets, it was decided to also run the SITA data with the "first leg start" option.

Taxi Times

To obtain the most accurate total fuel burn and emissions results possible, the option "airport specific" was used.
To reduce the potential error for taxi estimation, taxi times provided in the validation data have been entered into AEM3 before start of the validation runs to update the underlying Airport Taxi time dataset. As a consequence, taxi-out times used by AEM3 correspond to documented SITA taxi-out times in the available data sets. Taxi times for other airports

(not available in the SITA data) come from AEM3 system data. This system data is based on average taxi times declared by the airports to the CFMU.

Geographic Area

To ensure that all the points of the flights are taken into account and to remove any 4D region limitations, AEM3 was run for all the world (-180° < Long < 180° and -90° < Lat < 90°).

Flight Profile Completion

The validation was run with "no completion" and "complete all operations" options.

No Profile Completion

With this option, the flight profile data is used on an “as-is” base.
This allows a direct comparison of fuel burn information provided by the airlines against the estimations of AEM3. This raises an issue, however, since AEM3 uses BADA fuel burn information for very low altitudes with this option, yet it is a known weakness of BADA that its very low altitude data is not as accurate as its higher altitudes data. This can lead to a significant error for long legs flown at low altitudes.
SITA files only provide a rough description of the flight profiles (fewer than 10 points per flight on average) for each flight. As a consequence, the flight legs are long and much of the flight can be lost if no completion is requested, again implying a non-negligible potential for error. As fuel burn is only included in the SITA OFP data for complete missions, this option has not been used with SITA data.
The results corresponding to this option are shown as "NoAdd" in this report.

Complete LTO Operations Only

As the influence of LTO will be studied separately and "on a whole flight" basis, this option was not of interest for this validation. Furthermore, SITA provides fuel burn for the whole flight only excluding the taxi phases; this option can't be used with SITA.

Complete All Operations

This option can be applied to the FDR data to complete profiles which are not complete.
As explained before in the report, fuel burn is only indicated in the SITA OFP data for complete missions excluding taxis. Even when SITA files contain complete flight profiles, the flight description is often very rough (often zero or one point between departure airport and top of climb, and the same between top of descent and arrival airport). This option used together with SITA OFP data helps validate the fact that fuel/emissions for the flight taken as a whole are correctly estimated. As a consequence SITA files have been used with this option.
Climb and descent rates and ground speed are very important when using this option since they provide the basis for the trajectory estimation. For SITA data, many climb/descent rates had to be calculated since they were not provided in the original SITA files. The calculation is based on BADA aircraft performance data. BADA provides average climb and descent rates for many aircraft types and flight levels, but this data is accurate only for the specific weight of the aircraft used to produce the BADA data. Adapting these rates to the actual aircraft weights would be very time-consuming and problematic; therefore, average rates were used.
The results corresponding to this option are notified as "AddAll" in this report.

Output data analysis and results – Flight time and Fuel burn estimation with AEM3

Results of the comparisons between airline and AEM3 fuel burn estimation and flight duration are presented as follows:

$$\text{Duration Ratio} = \frac{\text{AEM3 flight duration}}{\text{Airline flight duration}} \qquad \text{Fuel Ratio} = \frac{\text{AEM3 fuel burn estimation}}{\text{Airline fuel burn information}}.$$

In an ideal case, Duration Ratio and Fuel Ratio would be equal to one. A value greater than one indicates that AEM3 overestimates the real duration or fuel burn.

Analysis of LTO Cycles

As explained above, the analysis of LTO cycles focuses on FDR data.
Very few datasets were available which provided details of fuel burn during LTO operations. These data sets have been converted to AEM3 LTO phases, i.e. Taxi Out, Take Off, Climb Out, Approach, Landing and Taxi In, based on a flight level repartition. Unfortunately no data was available after touchdown and the landing phase data were not exploitable. As a consequence, the analysis of LTO cycle is limited to the departure phases of the LTO cycle ("LTO Out") and approach.
The AEM3 fuel burn estimation during LTO calculation is based on fuel burn rates and times-in-mode, as documented in the *ICAO Exhaust Engine Emission Data Bank* from the engine certification tests. The motivation of this report is not to validate ICAO data but to estimate AEM3 error regarding operational data.

Duration of LTO Cycles

The following tables compare AEM3 duration and fuel burn values for LTO against real values from FDR data. They show that a determining criteria for AEM3 errors during LTO is the underlying duration of LTO operations. Any error on the duration parts of the LTO cycle will propagate into the fuel burn estimation. The error will further propagate into the emission estimations and here especially impact on the estimations for those pollutants which are mainly produced during phases of incomplete engine combustion; idle, approach, taxi operation etc. Duration of TakeOff, ClimbOut and Approach in AEM3 are extracted out of the *ICAO Exhaust Engine Emission Data Bank*. Taxi times applied are not extracted from ICAO data to be closer to reality (cf. see "Taxi Times" p20).
Large disparities between the AEM3 durations and the information extracted from the FDR data in terms of durations for TaxiOut and ClimbOut have been observed, as shown below:

AEM3 Phase	Number of flights	Fuel Ratio	Duration Ratio
TaxiOut	3827	1.79	1.62
TakeOff	3840	1.11	1.08
ClimbOut	3840	1.51	1.64
Approach	3837	1.89	1.04

Table 8: Duration and fuel ratio per LTO flight phase

This table illustrates the overestimation of duration for the ClimbOut phase, compared to certification times in the *ICAO Exhaust Engine Emission Data Bank*. Average TakeOff and Approach for the whole FDR traffic sample is close to ICAO/AEM values. The

duration ratio for TaxiOut indicates an important overestimation of the TaxiOut duration compared to average FDR TaxiOut duration. However TaxiOut is the longest LTO phase and is very dependent on factors like the airport or the traffic, which can explain the percentage of variation.

Fuel burn during LTO Cycle

The Ratio for fuel is almost identical than that for Duration for the phases "TaxiOut", "TakeOff" and "ClimbOut". This confirms the realism of the fuel flow information available in the ICAO Engine Exhaust Emissions Data Bank for these three operating modes.
This cannot be observed for Approach. Where the "Approach" duration seems to be overestimated by AEM3 by only 4%, the FuelRatio indicates an error of +89%. This could indicate that the fuel flow rates documented in the ICAO Engine Exhaust Emissions Data Bank are significantly higher than in real life for approach operations.
The following paragraphs break above information further down as a function of departure airport and/or aircraft type, depending on the criteria which has the more influence on the flight phase.

Take Off Phase

The dominating factor to determine the duration of TakeOff is assumed to be the aircraft type.

ACType	Number of flights	Fuel Ratio	Duration Ratio
A319-DAC	921	1.31	1.24
A320-DAC	911	1.28	1.21
A320-SAC	130	1.08	1.08
A321-DAC	475	1.33	1.09
A330	1316	1.05	0.94
A340	87	0.79	0.74

Table 9: Take Off per aircraft type

Take Off Phase Duration

AEM3 uses as duration for the TakeOff run the value for the TakeOff Mode from the ICAO Engine Exhaust Emissions Data Bank. This is defined by the ICAO LTO Engine Certification protocol as 0.7 minutes or 42 seconds.
The TakeOff duration is assumed to be purely a function of the aircraft type. If the average of TakeOff times indicated by AEM for the all traffic sample is close to the real FDR duration, break down per aircraft types in Table 9 highlights differences of -26 % to +24 %, equal to 31.08 and 52.08 seconds.
The TakeOff duration ratio over all flights and aircraft types is observed to be 1.08 (Table 8: Duration and fuel ratio per LTO flight phase). This seems to indicate that the ICAO Engine Certification duration for TakeOff Mode is 8 % higher than the average duration in reality.
In the context of global emission studies with AEM3 it can be concluded that fuel burn and emission estimations based on this duration input data error are 8 % too high for the TakeOff run.

Fuel burn during Take Off Phase

The fuel is naturally following this same tendency. However the fuel ratio is always higher than the duration ratio. In other words, take off fuel burn is overestimated by AEM for all the aircraft types under analysis.

Climb Out Phase

Mainly taxi times., but as well other phases of the LTO cycle seem to depend more on the airport and TMA design, e.g. SIDs, STARs, etc. than on the aircraft type. In the following table, each letter corresponds to a specific departure airport.

Dep Airport	Number of flights	Fuel Ratio	Duration Ratio
A	520	1.63	1.71
B	18	1.42	1.55
C	49	1.23	1.38
D	99	1.65	1.74
E	96	1.47	1.47
F	261	1.53	1.55
G	89	1.47	1.55
H	505	1.72	1.84
I	187	1.78	1.96
J	16	2.39	2.00
K	1830	1.47	1.63
L	126	1.28	1.43
P	23	1.73	0.93
T	21	1.30	0.83

Table 10:Climb Out per departure airport

Climb Out Phase Duration

ClimbOut duration is overestimated by 38 % to 100 % for all the airports of the study, with the exception of two airports (P and T) for which ClimbOut duration is slightly underestimated. As a result, depending on the airport the ClimbOut duration estimation error varies from -7 % to +100 %.
In the following table the fuel and duration ratio have been related, different than in the table above, to the aircraft type. The table indicates a different distribution of the ClimbOut duration error.

ACType	Number of flights	Fuel Ratio	Duration Ratio
A319-DAC	921	1.72	1.95
A320-DAC	911	1.65	1.83
A320-SAC	130	1.34	1.52
A321-DAC	475	1.72	1.61
A330	1316	1.41	1.47
A340	87	1.64	0.97

Table 11:Climb Out per aircraft type

Fuel burn during Climb Out Phase

With a duration ratio varying from -3 % to +95 % dependend on the aircraft type, the propagation into fuel burn leads to a non-homogeneous distribution.
Depending on airport and the aircraft type the comparison between fuel ratio and duration ratio varies significantly. The trend over the different departure airports (J, P, T) and aircraft types (A321-DAC, A340) can get become inverted; thus fuel burn can be under- or overestimated depending on the departure airport and the aircraft type.
Note that the A340 shows +64 % overestimation for fuel whereas -3 % (i.e. close to real life) for duration. This results in a huge overestimation of fuel for A340 for this phase of flight.
As a conclusion many parameters have a very strong impact on duration and fuel burn during ClimbOut which prevents making general assumptions on this phase. Table 8 "Duration and fuel ratio per LTO flight phase" indicates an average of 64 % duration overestimation against 51 % of fuel overestimation. This means that the error contribution purely of the fuel burn rates during ClimbOut has to be considered on average as underestimated by 13 %.

Approach Phase

Approach results vary depend on the airport and as well the aircraft type, as shown in the following tables.

Arr Airport	Number of flights	Fuel Ratio	Duration Ratio
A	432	1.42	1.05
B	18	1.36	0.91
C	40	1.58	1.02
D	94	1.85	1.00
E	101	1.94	0.80
F	248	1.41	0.81
G	91	2.35	1.12
H	463	1.27	0.85
I	189	1.51	1.00
J	16	2.43	1.14
K	2008	2.24	1.16
L	98	2.60	1.19
P	20	2.79	0.96
T	19	3.20	0.93

Table 12: Approach per departure airport

ACType	Number of flights	Fuel Ratio	Duration Ratio
A319-DAC	919	1.61	1.02
A320-DAC	910	1.49	1.07
A320-SAC	130	1.67	1.05
A321-DAC	475	1.65	1.10
A330	1317	2.13	1.02
A340	86	3.29	1.06

Table 13: Approach per aircraft type

Duration of the approach phase

Approach results are close to the real life times, as shown in Table 8 "Duration and fuel ratio per LTO flight phase". It seems that the duration, based on ICAO Engine Exhaust Emissions Data Bank certification times, varies between -20 % and +19 % depending on the arrival airport. It is limited to an overestimation of 2 % to 10 % when looking at the aircraft breakdown.

Fuel burn during approach phase

Fuel ratios for approach vary from +27 % up to 329 % depending on the arrival airport and the aircraft type. The table highlights disparities which makes it difficult to quantify an absolute error on fuel during approach.
These rather strong errors in the fuel flow comparing real operations fuel flows against the fuel burn rates of the ICAO Engine Exhaust Emissions Data Bank, could propagate into the emission indices as noted above.
This can not be verified in this project, but if confirmed, this would impact on the emission estimation all along the flights, since AEM3 using the BM2 approach, bases the calculation of emissions in altitude on the LTO ICAO Engine Exhaust Emissions Data Bank emission indices.

Taxi Out Phase

As TaxiOut times are not only based on certifications and as more validation data are available for TaxiOut than for other LTO phases, this paragraph will be more developed.

Taxi Out Duration in the FDR data

The FDR Taxi Out durations are very different from AEM3 system taxi durations for the same airports. On average, the duration of TaxiOut in FDR data is 630 seconds, against 1019 seconds in AEM3. Real taxi durations strongly depend on the size and runway configuration of the airports.

Dep Airport	Number of flights	Fuel Ratio	Duration Ratio
A	516	1.94	1.99
B	18	0.88	0.88
C	48	1.15	1.17
D	99	2.31	1.83
E	96	0.62	0.49
F	262	2.18	1.71
G	88	2.71	2.14
H	503	1.46	1.46
I	187	2.22	2.14
J	15	1.87	1.61
K	1825	1.67	1.55
L	126	2.24	1.86
P	23	1.74	1.70
T	21	2.13	2.18

Table 14: Taxi Out Per departure airport

With the exception of airports B and E, AEM overestimates the TaxiOut duration by +17 % to +218 %.

Note that this traffic sample holds data from only one airline flying from/to a limited number of airports. At its Hub airports it may use gates closer to the runway etc. which would reduce the duration of TaxiOut. As AEM3 TaxiOut durations have been collected through real data from several sources (airlines, airports), AEM3 system TaxiOut average durations are supposed to better reflect the possible variation in TaxiTimes concerning different airlines operating at the same airport platform than Table 14 "Taxi Out Per departure airport" implies.
When compared against certification of ICAO Engine Exhaust Emissions Data Bank (0 and 0), AEM3 underestimates the TaxiOut duration by an average of 11 %, which means that the difference between real life duration as observed in the FDR and ICAO figures is even bigger than the difference between FDR and AEM3 values.

Duration: SITA data

As SITA data hold TaxiOut durations for each flight, this information can be compared in this paragraph. The following figure compares the real SITA TaxiOut duration for different departure airports against the AEM3 system TaxiOut average duration. The ICAO Engine Certification duration for TaxiOut is also plotted as an indication 0.

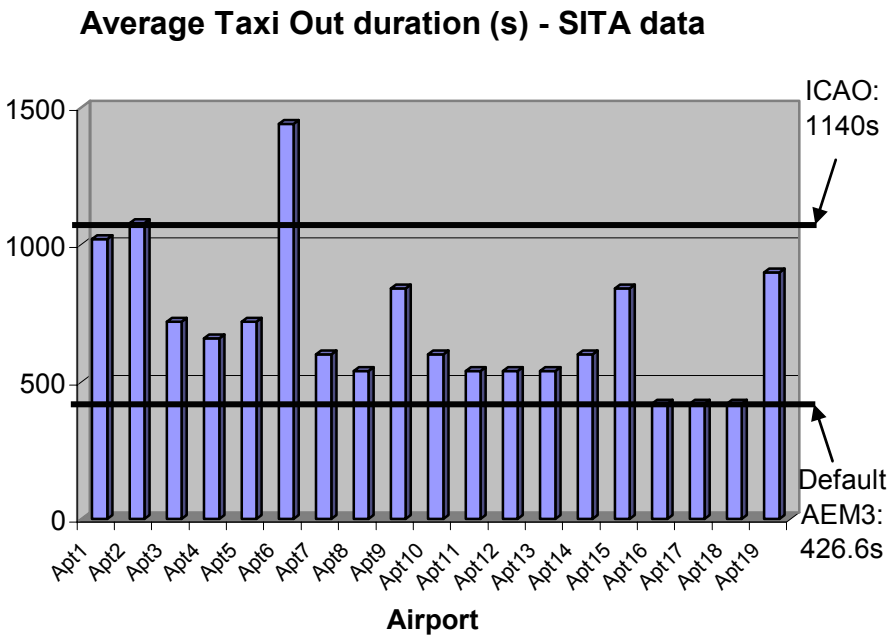


Figure 4: Average Taxi Out duration – SITA data

Figure 4: "Average Taxi Out duration – SITA data" indicates the AEM3 TaxiOut default duration to be significantly lower than the TaxiOut durations for the 19 airports included in the SITA data. Compared to that, the ICAO value for TaxiOut duration appears to be much too high for those 19 airports. Nevertheless, as explained earlier, the AEM3 default value is an average figure, based on airport TaxiOut information (operational & declared) of more than 3000 airports. This seems to assure that in average this value is close to reality. On the otherhand, this comparison shows that the ICAO duration for TaxiOut operation is much too high compared to real aircraft operation.

Fuel burn during TaxiOut

In a study, the flight time that AEM3 estimates for each complete flight profile includes the estimated times for taxi-in/-out. The taxi times used depend on the option chosen by the user: airport specific, CFMU or default value. This might result in differences between flight duration estimated by AEM3 and the real duration of a flight monitored by the airlines. Since the flight duration is the base for the later fuel and emission estimations, an error at this level will consequently propagate into those results. In particular TaxiOut is an important contributor to HC and CO emissions.
The error level visible in the fuel ratio follows error level observed for the duration ratio for the majority of the airports but a tendency cannot be extracted from Table 14: "Taxi Out Per departure airport". Fuel is overestimated for 8 airports and almost equal to reality (less than 5 % error) for 6 airports.

Analysis of LTO Cycles: Summary

Although the error rates seem to be very significant for the four LTO phases verified, the impact of the error of those LTO phases to the total fuel burn and emissions for a complete mission is nevertheless proportional to the ratio between the duration of those phases to the duration of the rest of the mission. Consequently their error contribution in the context of global emission studies can be considered as rather small. The increasing general interest in local air quality issues nevertheless motivate to invest in future further efforts in the LTO duration aspect.

The differences between AEM3 durations / fuel and FDR durations / fuel can be attributed to many factors, including:

Engines installed on aircraft may not be the engines used by AEM3 (cf. Table 5: " Aircraft Types for FDR Validation"). Potential errors resulting from the AEM3 aircraft/engine matches does not affect durations but may have an influence on fuel ratio.

Climatic conditions at airports may be significantly different from the ISA conditions used to test engines and create the ICAO database.

A sensitivity analysis for the impact of last aspect can be found in the annex of this report.

Real LTO durations depend on the airport and TMA design, the distance between the terminal and the runway system and the actual traffic situation on the taxi , runway and arrival and departure route system.

As AEM3 uses averages values for LTO, it is not expected to obtain an exact fit to reality for each aircraft movement at any airport in the world. Despite the observed error levels, it is concluded that the AEM3 concept to functionally relate LTO durations to airports (and later aircrafts) allows fuel burn and emission estimations to be significantly more realistic than the use of unique values for the entire traffic sample as in earlier models and project.

Flight Profile Analysis: Flight Duration

To perform its calculations, AEM3 makes the following general assumptions:
International Standard Atmosphere (ISA) temperatures
Mass of the aircraft is constant over the entire flight
Direct route between 2 flight points, with conservation of attitude, ground speed, etc
No wind
The following paragraphs aim to verify the quality of the overall fuel burn and emission estimation quality over the complete mission profile and tries at the same time to indicate the influence of the above parameters on the calculation.
As flight duration is a key factor in fuel burn and emissions estimation, the quality of flight duration estimation by AEM3 has to be studied before focusing on fuel burn or emissions estimation.
The duration ratio indicated in the chapter is the ratio obtained with "AddAll" option. Duration ratios with "NoAdd" option would always be 1 since with this option, AEM3 uses the FDR durations.
Note that the duration difference comes from the portion of the flight not described in the input data. This portion is composed by: LTO phases, flight's profile between the end of ClimbOut and the first point in the input "Flight" file, flight's profile between the last available point in the input "Flight" file and the beginning of approach.
The ratios presented in the following tables are correct for the validation data sample only. They are not intended to validate duration since the duration estimated by AEM3 depends very strongly on the quality of the input "Flight" file and in particular on the climb/descent rate and ground speed values and the percentage of the flight profile included in the input data. Duration ratios are intended only to better estimate the fuel error; they should not be taken as absolute numbers.

FDR Mission Duration

The duration ratio for the total FDR traffic sample is 1.02. This means that the total flight duration indicated by AEM3 for 3833 flights under study is 2 % higher than the real total flight duration. The influence of various criteria is discussed in the paragraphs below.
The breakdown by aircraft type presented in Table 15 below highlights disparities between aircraft, even if an overestimation of flight duration is observed for all the aircraft types under study. The completion of the raw input flight profiles leads to a slight overestimation of the mission duration which varies between + 1% and + 8%.
The reason why aircraft type has an influence on flight duration is that climb/descent rates and ground speed values vary with the aircraft type, its actual takeoff weight and meteorological conditions. As a consequence, the completion of flight profile by AEM3 differs depending on the aircraft performances.

ACType	Number of flights	Duration Ratio
A319-DAC	917	1.08
A320-DAC	910	1.07
A320-SAC	128	1.02
A321-DAC	475	1.07
A330	1317	1.01
A340	86	1.01

Table 15: Duration ratio per aircraft type (FDR)

For this reason, the following breakdowns are performed by aircraft type. A breakdown per aircraft type and distance range (Table 16) clearly shows that the duration ratio becomes smaller when the distance flown grows. Indeed for long flights the portion of the flight for which AEM3 estimates duration is almost negligible compared to the known portion of flight. The impact of AEM3 duration estimation in this case is less important.

ACType	Distance Range	Avg Distance (km)	Number of flights	Duration Ratio
A319-DAC	Short	603	911	1.08
A320-DAC	Short	683	907	1.07
A320-SAC	Short	178	26	1.19
	Medium	3118	102	1.02
A321-DAC	Short	703	475	1.07
A330	Short	230	13	1.16
	Long	6490	1304	1.01
A340	Short	230	2	1.15
	Medium	4762	43	1.01
	Long	9026	39	1.00

Table 16: Duration ratio per aircraft type and distance range (FDR)

A breakdown by aircraft type and take-off weight (Table 17) shows the same tendency: duration ratio is higher for lighter aircraft regardless of the aircraft type. This is a logical result: with the same engine setting, LTO operations (especially take-off and climb-out) and the climb phase are longer for heavy aircraft. AEM3 duration overestimation is thus less important for heavy aircrafts.

ACType	BADA Nominal weight	Weight Category	Number of flights	Avg TO Weight (kg)	Duration Ratio
A319-DAC	60000	Low	3979	56782	1.08
		Medium	1442	59924	1.08
		High	81	63780	1.07
A320-DAC	62000	Low	2949	60880	1.07
		Medium	1703	61784	1.07
		High	808	65991	1.07
A320-SAC	62000	Low	302	67619	1.02
		Medium	154	65133	1.03
		High	312	72397	1.02
A321-DAC	72000	Low	1040	70488	1.07
		Medium	420	67186	1.07
		High	1390	72767	1.07
A330	190000	Low	55	167660	1.02
		Medium	1381	205601	1.01
		High	6466	211266	1.01
A340	200000	Low	172	117412	1.01
		Medium	1	71741	1.14
		High	343	117545	1.01

Table 17: Duration ratio per aircraft type and take-off weight (FDR)

SITA data

The overall fuel ratio for SITA data is 1.16 for 3790 flights. With the exception of the B742, a breakdown per aircraft type (Table 18) shows that the duration ratio is higher with SITA data than with FDR data. This is due to the fact that SITA flight profile data available to this project is of much lower granularity than FDR profiles, generally including only 3 to 31 points. This also affects the fuel burn results, as described below.

ACType	Number of flights	Duration Ratio
A306	193	1.13
A310	200	1.21
A319	418	1.12
A320	697	1.11
A321	504	1.10
A340	5	1.19
B733	942	1.20
B735	824	1.14
B742	6	1.08
B744	1	1.32

Table 18: Duration ratio per aircraft type (SITA)

However the tendency for a breakdown depending on the distance (Table 19) is the same for FDR and SITA data: AEM3 flight completion has less impact on the duration of long flights.

Distance Range		Number of flights	Avg Of Distance KM	Duration Ratio
Between (km)	And (km)			
0	500	2717	374	1.17
500	1000	780	639	1.19
1000	1500	133	1217	1.08
1500	2000	81	1708	1.02
2000	5000	79	2638	0.98

Table 19: Duration ratio per distance range (SITA)

Flight Profile Analysis: Fuel Burn

FDR Data

The following tables highlight the influence of various factors on the fuel ratios. Ratios are indicated for both options "AddAll" and "NoAdd". The duration ratio for the "AddAll" option is indicated again in below tables to help understand the fuel ratio.
Important note: Errors in detailed real fuel burn indicated in FDR data have been highlighted, especially for A320-SAC. For this reason, no fuel ratio for NoAdd option is indicated for A320-SAC in this section of the report. Even if no obvious error has been reported for other aircrafts, this study will rely on AddAll option ratios. Indeed real FDR fuel burn values for complete flights used for AddAll option comparison seem to be correct.

The fuel ratio for the overall traffic sample with "AddAll" option is 1.01. Seeing that the duration error with this option is around +2 %, the resulting fuel error can be considered as an underestimation of fuel by 1 %. On the other hand, the fuel burn is underestimated by 3 % with "NoAdd" option. This difference can be attributed entirely to the addition of LTO phases in the “AddAll” option (see "Analysis of LTO Cycles").

Fuel Burn by Aircraft type

Table 20 below shows fuel burn ratios as a function of aircraft type.

ACType	AddAll			NoAdd	
	Number of flights	Fuel Ratio	Duration Ratio	Number of flights	Fuel Ratio
A319-DAC	917	1.03	1.08	919	0.92
A320-DAC	910	0.98	1.07	910	0.89
A320-SAC	128	0.92	1.02	128	
A321-DAC	475	1.00	1.07	475	0.88
A330	1317	1.01	1.01	1318	0.98
A340	86	0.99	1.01	87	0.98

Table 20: Fuel ratio per ACType

The fuel ratio indicated for the NoAdd option signals that the underlying BADA fuel burn models seem to underestimate the fuel burn (depending on the aircraft type) between 2 and 11 % based on a nominal weight assumption.
The completion of the raw input flight profiles combined with the underestimation of the fuel flow as indicated above leads to a final fuel burn estimation error of AEM3 which varies between -8 to +3 %.
With a duration ratio of 1, the fuel ratio for "AddAll" option would read -10 to 0 %, which confirms that AEM3 underestimates the fuel burn during all flight phases except the LTOs.
Beside variation in weight, the difference in aircraft/engine combinations as available with the BADA models and the aircraft/engine combinations found in the FDR data also affect the quality of the results. For example, the A320: the A320-SAC is designed to burn less fuel than the A320-DAC, but it is represented by the same aircraft/engine within AEM3. Thus the fuel consumption shown by AEM3 is the same for the 2 aircraft but different in FDR data. This explains why the ratio "AEM3 fuel/FDR fuel" is lower for A320-SAC than A320-DAC. In the current version of AEM3v1.5, the same unique engine type is linked to all the aircrafts of a specific type appearing in the traffic sample. This ”AEM engine” may differ for a number of aircrafts of this specific type from the real engine installed on the aircraft. A concept to overcome this limitation in a future version of AEM3 is already been worked out.

Fuel Burn by City Pair

The following tables document a dependency between the city pairs and mission distance flown to the fuel burn and duration results accuracy of AEM3.
Table 21 shows the influence of distance range on aircraft efficiency. The trend varies greatly, depending on the mission length. Long flights with a stop over versus short flights. An important discrepancy to note here is the A320-SAC, A330 and A340 flying extreme short distances; these aircraft are designed for medium to long range missions, which is reflected in their BADA fuel flow models. Consequently the error level for such aircraft types performing such short, low altitude missions is without surprise relatively high.

Table 21 also shows a few aircraft flying from and to the same airport. The motivation for such flights might be crew training or technical check flights. The fuel ratios for this kind of special mission are meaningless in the context of global emission studies and for this validation project.

ACType	City Pair	Distance (km)	AddAll			NoAdd	
			No. of flights	Fuel Ratio	Duration Ratio	No. of flights	Fuel Ratio
A319-DAC	K / A	856	206	1.00	1.06	206	0.92
	K / H	478	420	1.06	1.10	421	0.93
	K / I	605	285	1.02	1.08	285	0.90
	K / K		6	0.97	1.06	7	0.87
A320-DAC	K / A	856	472	0.96	1.06	472	0.89
	K / H	478	373	1.00	1.10	373	0.88
	K / I	605	62	0.99	1.08	62	0.88
	K / K		3	1.01	1.05	3	0.98
A320-SAC	B / C	106	11	1.29	1.26	11	
	K / J	230	15	1.11	1.16	15	
	K / B	3143	27	0.91	1.01	27	
	K / C	3109	75	0.92	1.02	75	
A321-DAC	K / A	856	273	0.99	1.06	273	0.89
	K / H	478	173	1.04	1.09	173	0.88
	K / I	605	29	0.99	1.08	29	0.83
A330	K / L	6544	224	0.99	1.01	225	0.96
	K / D	6006	193	1.02	1.01	193	1.00
	K / G	7126	180	0.99	1.01	180	0.96
	K / J	230	13	1.49	1.16	13	1.17
	K / F	6356	510	1.02	1.01	510	0.99
	K / E	6669	197	1.01	1.01	197	0.98
A340	J / J		1	1.31	1.08	1	1.06
	K / T	9026	39	0.96	1.00	40	0.96
	K / P	4762	43	1.05	1.01	43	1.01
	K / J	230	2	1.36	1.15	2	1.38
	K / K		1	0.89	1.10	1	0.99

Table 21: Fuel ratio per city pair

Fuel Burn by Distance Range

Another breakdown considers the distance range of the flights. Three distance ranges have been defined as follows
Short haul: less than 1000 km
Medium haul: between 1000 and 5000 km
Long haul: more than 5000 km
These ranges have been chosen to keep a significant number of flights in each range, since the data sample consists only of data between 21 airports, which does not provide a broad range of distances to study.
Table 22 tends to confirm that AEM3 error increases when aircraft are not flying optimised distances. Each type of commercial aircraft is designed for a specific mission range. Flying outside this specific mission range decreases aircraft efficiency and leads to increased error level when comparing against a mathematical nominal aircraft performance and fuel burn model which is based on the typical range assumption.

ACType	Distance Range	Avg Distance (km)	AddAll			NoAdd	
			Number of flights	Fuel Ratio	Duration Ratio	Number of fights	Fuel Ratio
A319-DAC	Short	603	911	1.03	1.08	912	0.92
A320-DAC	Short	683	907	0.98	1.07	907	0.88
A320-SAC	Short	178	26	1.16	1.19	26	
	Medium	3118	102	0.91	1.02	102	
A321-DAC	Short	703	475	1.00	1.07	475	0.88
A330	Short	230	13	1.49	1.16	13	1.17
	Long	6490	1304	1.01	1.01	1305	0.98
A340	Short	230	2	1.36	1.15	2	1.38
	Medium	4762	43	1.05	1.01	43	1.01
	Long	9026	39	0.96	1.00	40	0.96

Table 22: Fuel per distance

The A319, A320 and A321 are dedicated to medium range missions whereas the A330 and A340 is optimised for long haul flights. The following table indicates the maximum range at full load for aircraft types studied. These data come from the web site of the airline which provided FDR data. Obviously the distance which can be flown is longer if the aircraft payload is lighter.

ACType	A319	A320	A321	A330	A340
Max. range with full load	3000 km	3650 km	3200 km	8400 km	10500 km

Table 23: Maximum distance range at full load

A reason for AEM3 error is that BADA data used in AEM3 consider an average aircraft weight accurate for "standard optimised" missions. The quantity of fuel tanked depends on the mission length and the stop over.
Furthermore, short distance flights are operated at lower altitudes. For example the maximum flight level between airports B and C does not exceed 70 (about 7000ft). Fuel flow indicated by BADA at low altitudes for medium / long haul aircrafts are high compared against fuel flow at high altitudes, which accentuates the error influence. The case of A340 flying 9026, 4762 and 230 km illustrates perfectly this phenomenon. The shorter mission missions A340 performs, the worse is the fuel ratio.
At least the influence of LTO fuel burn overestimation is more important for short distances while it is almost negligible for long missions.
Fuel ratio for the entire flight profile with the duration error varies from -9 % to +49 % depending on the aircraft. Without duration error, these percentages would vary from -11 % to +33 %. Even if these variations seems important, the influence of distance on fuel burn estimation is respected.

Fuel Burn by Take-Off Weight

Another important factor in fuel consumption is the actual weight of the aircraft.
The underlying BADA data provides fuel burn rates for low, nominal and heigh aircraft weights. Low weight is defined by BADA as 1.2 * the Operating Empty weight (OEW). High weight is defined as the aircraft Maximum Take-Off Weight (MTOW). Nominal BADA aircraft weight is defined as OEW + 0.7 * (MTOW – OEW).

With the current version 1.5 of AEM3 under validation in this project, nominal BADA fuel flow rates are applied to all flights. Low and high weight BADA fuel flow figures are not considered.
To further compare the influence of weight variation of real flights to the results estimated by AEM3, three categories of TakeOff weight have been defined to group the results: low, medium, high. The categories have been estimated based on BADA weights.
The difference (MTOW – 1.2 × OEW) has been divided into equal 3 parts called in below table Low, Medium and High:

- Low = 0 to 33 % of the difference
- Medium = 33 to 66 % of the difference
- High = 66 to 100 % of the difference

The formula (MTOW - 1.2 × OEW) has been used to determine the potential mission weight range per aircraft type instead of (MTOW – OEW) since aircraft can not be operated at their OEW.

ACType	Low <---------- ->		Medium <---------- ->		High <---------- >
	BADA Low Weight 0 %	Limit Inf 33 %	BADA Nominal Weight	Limit Sup 66 %	BADA High Weight 100 %
A319	48000	55333	60000	62667	70000
A320	50160	57940	62000	65720	73500
A321	57360	65907	72000	74453	83000
A330	150000	176667	190000	203333	230000
A340	156000	188500	200000	221000	253500

Table 24: Weight categories for FDR data (kg)

The table below shows the minimum and maximum take-off weight provided with FDR data for the flights in the study.

ACType	Minimum TOW	Maximum TOW
A319-DAC	48335	66479
A320-DAC	51456	68365
A320-SAC	48335	76639
A321-DAC	58713	79252
A330	138548	230574
A340	143482	274266

Table 25: Traffic Sample Weight Limits

Note that the weight information found in the FDR data exceeds the weight limit envelope as defined in the BADA aircraft performance tables for the aircraft types A320-SAC, A330 and A340. This is the case, both for minimum and maximum values.
As shown in Table 5, section "Aircraft Types", AEM3 uses BADA (Version 3.5) equivalent of the aircrafts in the initial files. BADA performance table are based on TOW.

Calculations in AEM3 are performed with the "nominal" mass. Heavy aircraft are expected to burn more fuel than AEM3 indicates, as opposed to light aircraft which should use less fuel than estimated by AEM3.
In the context of global emission studies, this variation should not have significant impact if the “nominal” weight and fuel burn corresponds to a high extent to the average real operating weight of the flights under analysis.
In Table 26, weight information for each flight has been considered to evaluate the influence of real weight against AEM3 normalised reference weight.

ACType	BADA Nominal weight	Weight Category	AddAll				NoAdd		
			No. of flights	Avg TO Weight (kg)	Fuel Ratio	Duration Ratio	No. of flights	Avg TO Weight (kg)	Fuel Ratio
A319-DAC	60000	Low	3979	56782	1.04	1.08	259	53620	0.93
		Medium	1442	59924	1.02	1.08	580	58720	0.91
		High	81	63780	1.00	1.07	80	63722	0.92
A320-DAC	62000	Low	2949	60880	0.99	1.07	175	56305	0.90
		Medium	1703	61784	0.98	1.07	546	62038	0.89
		High	808	65991	0.95	1.07	189	66768	0.87
A320-SAC	62000	Low	302	67619	0.93	1.02	2	48770	
		Medium	154	65133	0.94	1.03	36	61648	
		High	312	72397	0.91	1.02	90	72477	
A321-DAC	72000	Low	1040	70488	1.00	1.07	90	63890	0.89
		Medium	420	67186	1.02	1.07	231	70150	0.89
		High	1390	72767	0.99	1.07	154	76778	0.87
A330	190000	Low	55	167660	1.12	1.02	13	147804	1.17
		Medium	1381	205601	1.02	1.01	325	196896	1.02
		High	6466	211266	1.01	1.01	980	215130	0.97
A340	200000	Low	172	117412	0.99	1.01	87	117580	0.98
		Medium	1	71741	1.61	1.14			
		High	343	117545	0.99	1.01			

Table 26: Fuel ratio per Take Off Weight

The tendency is respected for AddAll option.
The influence of the use of a nominal weight assumption as in AEM3 compared to real aircraft TOW becomes visible in a result variation between -7% and +4% around the real observed fuel burn as a function of the aircraft type.

The following Table 27 shows fuel burn result variation as a function of distance and weight on a aircraft type base.

ACType	Dist Range	Weight Category	Avg Dist-ance (km)	AddAll				NoAdd		
				No of flights	Avg TO Weight (kg) in category	Fuel Ratio	Dura-tion Ratio	No of flights	Avg TO Weight (kg)	Fuel Ratio
A319-DAC	Short	Low	549	257	53625	1.06	1.08	257	53625	0.93
		Medium	615	577	58728	1.02	1.08	578	58729	0.91
		High	691	77	63703	1.00	1.07	77	63703	0.91
A320-DAC	Short	Low	630	175	56305	1.01	1.08	175	56305	0.90
		Medium	675	543	62049	0.98	1.07	543	62049	0.89
		High	758	189	66768	0.94	1.07	189	66768	0.87
A320-SAC	Short	Low	230	2	48770	1.31	1.18	2	48770	
		Medium	171	23	60994	1.15	1.19	23	60994	
		High	230	1	65753	1.10	1.19	1	65753	
	Medium	Medium	3119	13	62805	0.96	1.01	13	62805	
		High	3118	89	72553	0.91	1.02	89	72553	
A321-DAC	Short	Low	632	90	63890	1.04	1.07	90	63890	0.89
		Medium	702	231	70150	1.01	1.07	231	70150	0.89
		High	746	154	76778	0.97	1.06	154	76778	0.87
A330	Short	Low	230	13	147804	1.49	1.16	13	147804	1.17
	Long	Medium	6349	325	196896	1.05	1.01	325	196896	1.02
		High	6537	979	215140	1.00	1.01	980	215130	0.97
A340	Short	Low	230	2	75365	1.36	1.15	2	75365	1.38
	Medium	Low	4762	43	108876	1.05	1.01	43	108876	1.01
	Long	Low	9026	39	130732	0.96	1.00	40	130766	0.96

Table 27: Fuel ratio per Take Off Weight and Distance Range

This table indicates the tendency for all distance / weight combinations and shows that AEM3 reacts to the variation of these two parameters as expected.

SITA data

The following analysis is based on 3790 SITA Operational Flight Plans. Results are presented in following table as a function of the aircraft type.
As fuel information indicated in the SITA data was only given as a total for the whole flight (except taxi phases) the SITA profiles have been completed by using the AEM3 option "Add all operations".
Since the departure time in many records was unusable, the analysis was done using the AEM3 option "first leg start".
Results with this combination of options ("add all operations" + "first leg start") are expected to be of less high quality than with other options. This is due to the estimation of take-off time plus the re-creation of the profile from this estimated time. Flight profiles are no longer exactly like initial SITA profiles which increases the fuel burn (and emissions) estimation error.

ACType	Number of flights	Fuel Ratio	Duration Ratio
A306	193	1.17	1.13
A310	200	1.29	1.21
A319	418	1.20	1.12
A320	697	1.14	1.11
A321	504	1.22	1.10
A340	5	1.30	1.19
B733	942	1.20	1.20
B735	824	1.30	1.14
B742	6	1.12	1.08
B744	1	1.45	1.32
Total	*3790*	*1.24*	*1.16*

Table 28: Fuel ratio per ACType

The duration applied for LTO operations by AEM3 under FL 30 are fixed values taken from the ICAO Engine Exhaust Emission Certification protocol. As a consequence SITA flight duration may differ from AEM3 re-calculated flight duration, which explains a time ratio different from 1. The above table indicates that AEM3, when used with the “Add all” option together with the “first leg start” option, seems to overestimate flight duration by 8-32 % depending on the aircraft with an average of 16 % overestimation.
Fuel burn seems to be overestimated by 12-45 % (average of 24 %) for the limited list of Aircraft types represented in the above table. This could be interpreted to mean that the overestimation added solely by the underlying BADA fuel flow model for the aircraft types in question lies in the order of 8 %.

Departure Airport	Number of flights	Fuel Ratio	Duration Ratio
S	1	1.66	1.34
K	95	1.25	1.16
A	1332	1.17	1.15
N	39	1.28	1.17
D	220	1.29	1.17
G	208	1.24	1.14
C	414	1.22	1.13
B	589	1.19	1.10
M	68	1.34	1.19
J	96	1.33	1.22
F	204	1.27	1.14
E	346	1.29	1.18
H	92	1.27	1.18
L	67	1.24	1.17
R	4	1.24	1.17
Q	7	1.35	1.25
P	5	1.17	1.13
I	3	1.14	1.17

Table 29: Fuel ratio per departure airport

The table above shows a strong variation in the results, depending on the departure airport, which underlines the hypothesis that the main error influence is caused by the completion of the SITA flight profile data. The results for the airports (with a statistical base of at least 10 flights) indicate AEM3 overestimation from +10 to +22 % for duration and between +17 and +34 % for fuel. If first error is deduced from the fuel burn results the table indicates an remaining fuel burn overestimation between +2 and +15%.

Distance Range		Number of flights	Avg Of Distance KM	Fuel Ratio	Duration Ratio
Between (km)	And (km)				
0	500	2717	374	1.27	1.17
500	1000	780	639	1.21	1.19
1000	1500	133	1217	1.16	1.08
1500	2000	81	1708	1.07	1.02
2000	5000	79	2638	0.97	0.98

Table 30: Fuel per distance

AEM3 overestimates LTO fuel and duration in the case of the SITA data with Addall option and first leg start. This becomes visible in the above table, which indicates a clear trend that the longer the flight is, the more the LTO effect is reduced. For long flights with a distance range between 2000 and 5000 km, fuel burn and duration ratios are very close to 1. For this range AEM3 underestimates duration and fuel by 2 and 3 %.

SITA Versus FDR Results

The aim of this section is to deduce the error impact of the low granularity flight profiles and the flight profile completion included with the SITA AEM test data. AEM3 SITA results are compared against AEM3 FDR results for identical aircraft types: A319, A320, A321 and A340.
It is hoped that the information extracted from this comparison of aircraft types which appear in the SITA and as well in the FDR data allows a more reliable error estimation for those aircraft types fuel burn models for which no operational airline FDR data for direct validation was available.
With the same options, the average difference of fuel burn against AEM3 are as follows:

	FDR	SITA	Difference	Number of flights (SITA)
A319	+3 %	+20 %	17 %	418
A320	-3 %	+14 %	17 %	697
A321	0 %	+22 %	22 %	504
A340	-1 %	+30 %	31 %	5

Table 31: FDR and SITA difference against AEM3

This seems to indicate that the lower fidelity profiles available with the SITA OFP data are responsible for a fuel burn estimation error between 17 and 22 %, with a resulting weighted average 18.6 %. If this error estimation is deduced from the results presented in Table 28 to eliminate the impact of unsatisfactory flight profile data, a rough indication of the error levels purely coming from the underlying BADA fuel burn model can be extracted.
Table 32 indicates the resulting error estimation per aircraft type fuel burn model:

ACType	Number of flights	Fuel Ratio
A306	193	0.98
A310	200	1.10
A319	418	1.01
A320	697	0.95
A321	504	1.03
A340	5	1.11
B733	942	1.01
B735	824	1.11
B742	6	0.93
B744	1	1.26
Total	*3790*	*1.05*

Table 32: Corrected fuel ratio per ACType

The resulting estimation of the AEM3 error varries between -7 and +11 % with an average of 5 % overestimation of fuel burn for these aircraft types. (The results for the aircraft type B744 are not included in the average because they are based on only 1 flight).
However this indirect estimation of AEM3 error for the aircraft types for which no FDR data was available is only thought to be a first indication. Direct validation against FDR data should be undertaken in futur to test the current results.

Flight Profile Analysis: Fuel Flow

Evolution of Fuel Flow

The evolution of fuel flow versus time for typical 600 km, 3300 km and 6600 km long missions is shown in Figure 5 to Figure 7. In each figure, the blue curve represents fuel flow estimated by BADA in AEM3; the pink curve represents the real fuel flow provided with FDR data; and the dotted curve shows the flight profile. The scale used for this third curve refers to the secondary axis on the right of the plot.
These graphs show that the evolution of AEM3 fuel flow is similar to reality.
Punctual differences like on Figure 5 at 1200 s and 3800 s are due to the fact that BADA provides fuel flow for each leg based on the attitude of the leg, independent of the following legs, and the value varies widely in BADA depending on the attitude. A non-negligible error may appear and impact a particular emissions estimation in the case of long climb/descent legs at a very low rate of climb / descent. The peak at 1200 s corresponds to a short descent phase while a short climb phase creates the peak at 3800 s. This trait is explained in further detail in the section "Macroscopic Approach: Emissions Validation" section "FDR data".
Figure 6 indicates a gap in time between the two fuel flow curves. This is due to a difference in taxi duration estimation by AEM3 different than the real taxi duration.
The fluctuation of fuel flow during descent phases (shown in Figure 7) is due to fuel flow values in the BADA database. BADA data for this aircraft at low altitude seems to be overestimated.

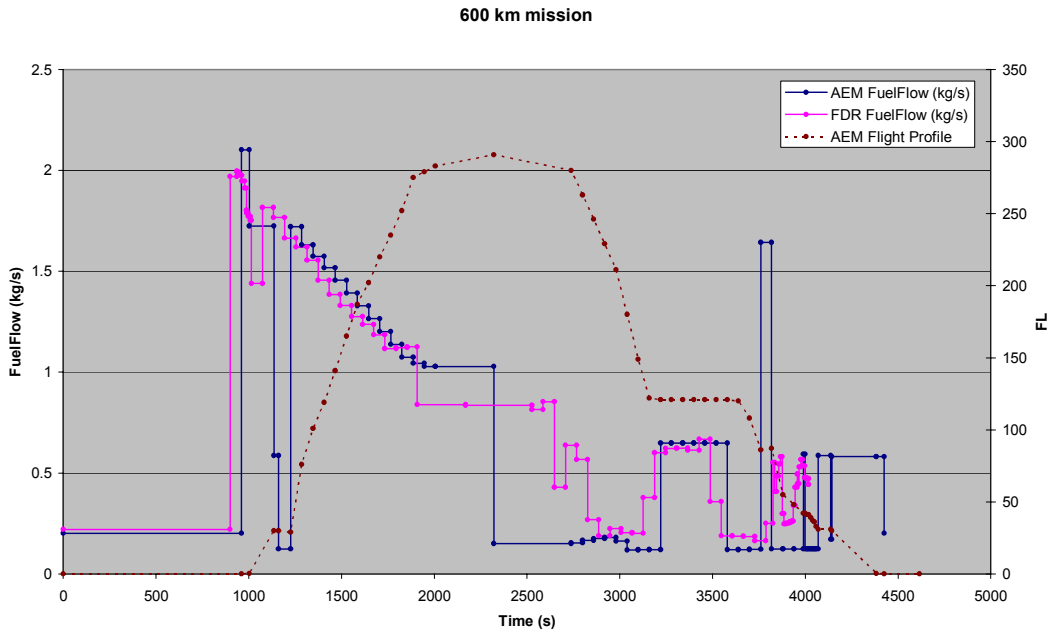


Figure 5: Evolution of fuel flow for a 600 km mission

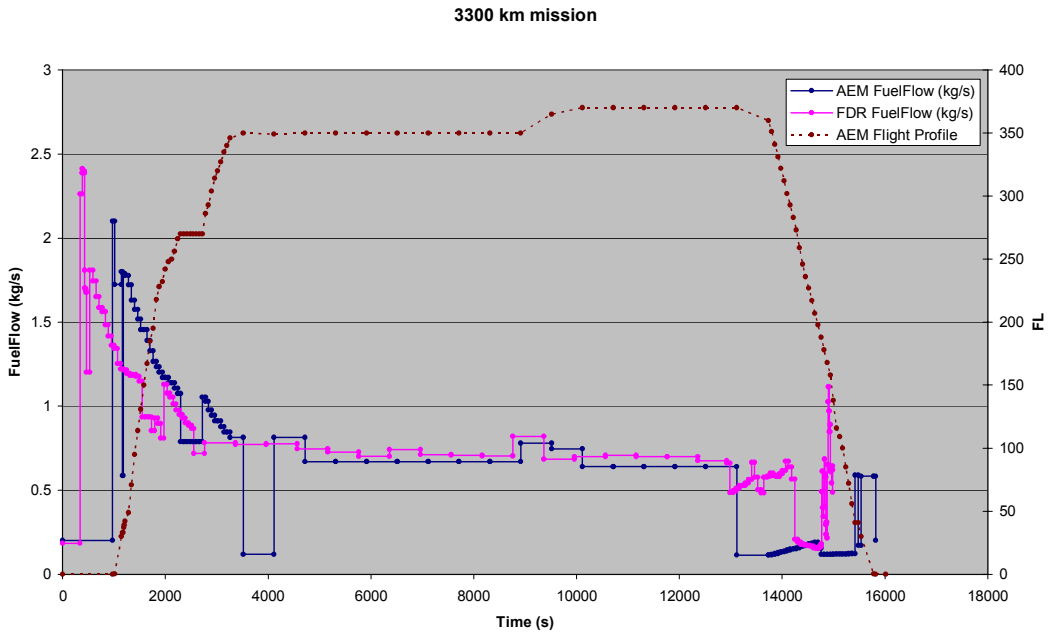


Figure 6: Evolution of fuel flow for a 3300 km mission

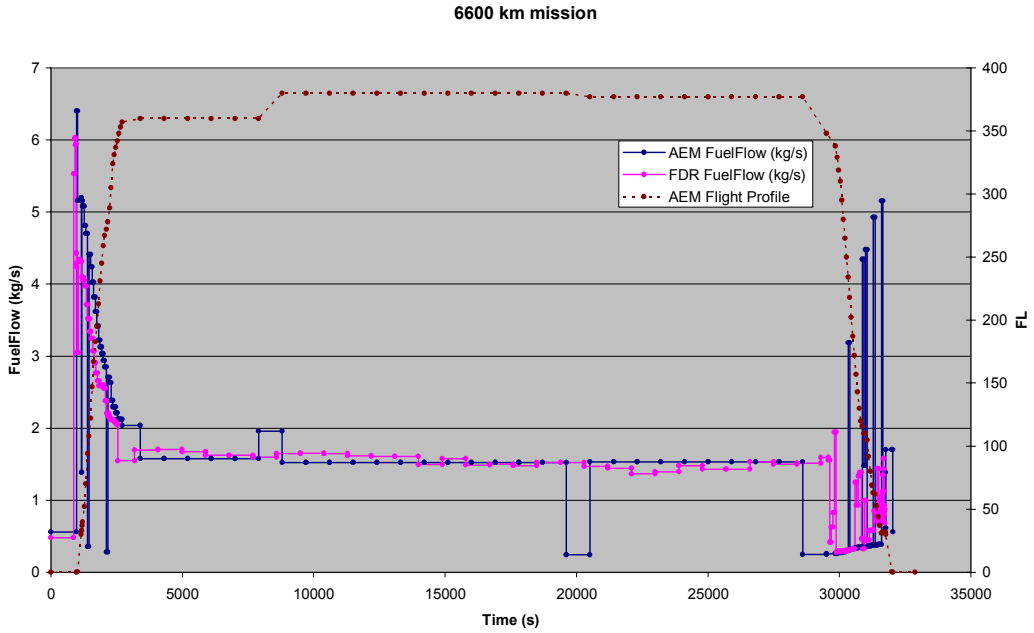


Figure 7: Evolution of fuel flow for a 6600 km mission

Fuel Flow Limits

Limits of BADA fuel flow as absolute values has been compared against the real limits of fuel flow for each aircraft. The comparison is shown in Figure 8 to Figure 12.
In each figure, minimum and maximum real fuel flow values for the full traffic sample (one aircraft type per figure) are shown along with the BADA values. These figures show that in reality aircrafts are operating with higher and as well with lower fuel flow rates than documented by BADA and ICAO. The situation for low fuel flow is even worse for ICAO data than for the BADA data.
This observation is valid for each aircraft type analysed in the study. As AEM3 bases its fuel burn calculation on fuel flow values from BADA database, fuel flows and consequently fuel burn indicated by AEM3 have some degree of error imposed by the BADA limits.
This error propagates into emissions estimation through the Boeing Method 2. Indeed BM2 compares in-flight BADA fuel flow against fuel flow from ICAO Engine Emissions Data Bank during LTO (idle, take-off, climb-out, approach) to estimate emissions for one leg. If in-flight fuel flow indicated by BADA is lower than the minimum fuel flow documented by the ICAO Engine Emissions Data Bank for the corresponding engine, AEM3 uses the emissions indices corresponding to this lowest ICAO fuel flow. If this would not be done and the fuel flow function of ICAO would be extrapolated beyond the lowest limits extreme overestimations of HC and CO would appear.
To visualize aircraft affected by this problem, minimum and maximum fuel flow values from ICAO Engine Emissions Data Bank for the engine corresponding to the BADA aircraft has been added to Figure 8 to Figure 12. When available directly in the ICAO Engine Emissions Data Bank, fuel flow limits for the real engine indicated by the FDR provider have been shown for reference.
These graphs indicate that all aircrafts in this study are affected by this problem. Where for low real fuel flows HC and CO estimations would be affected, high fuel flow rates outside the known BADA and ICAO limits risk to induce an overestimation of NOx. This issue is examined more closely in the next section.
Bear in mind, however, that these figures deal with extreme fuel flow limits and are intended to explain periodic variation of AEM3 results against “real” (FDR) data – thus this problem concerns only some extreme points of some flights.

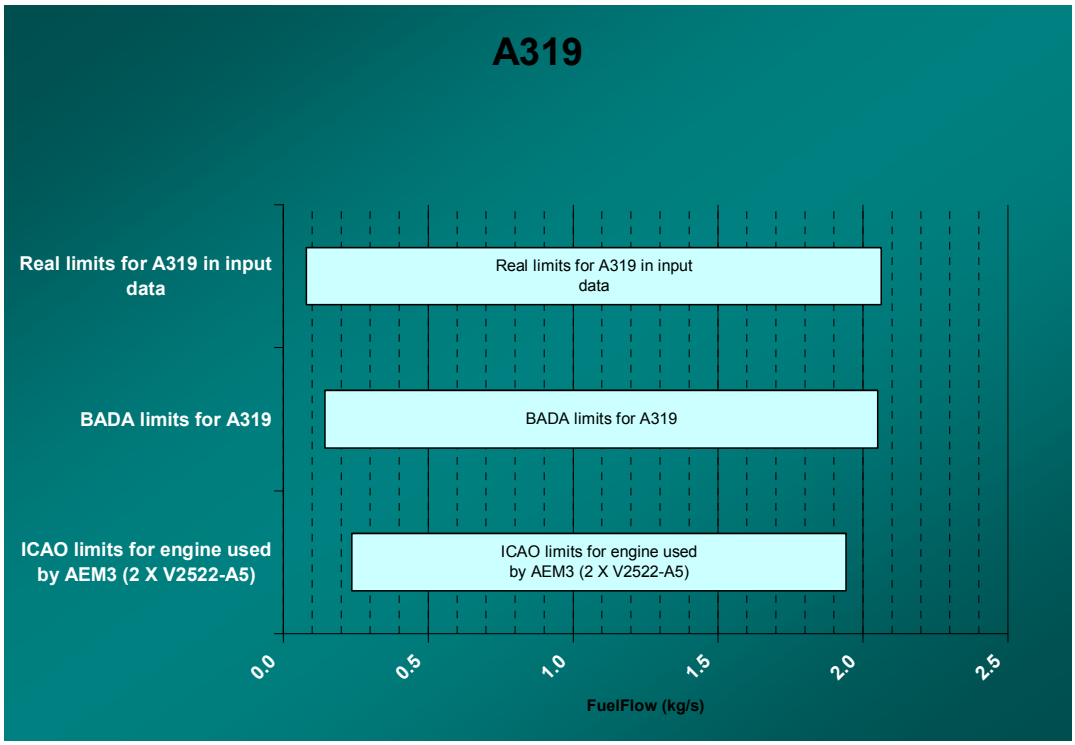


Figure 8: Fuel flow limits – A319

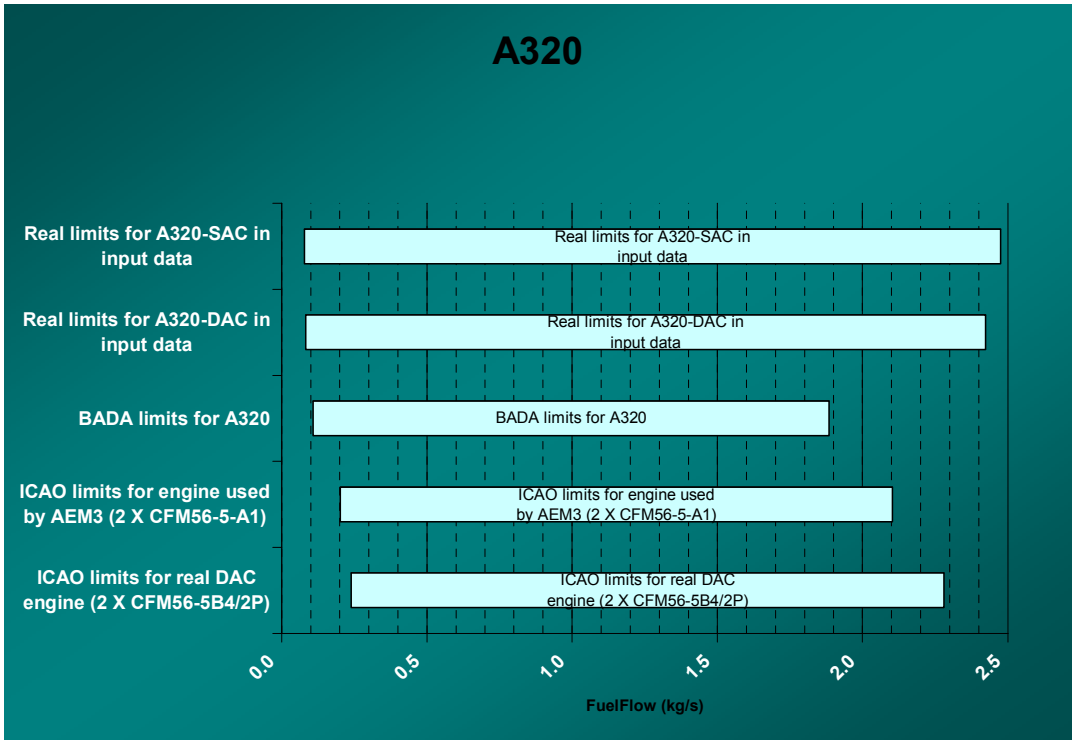


Figure 9: Fuel flow limits – A320

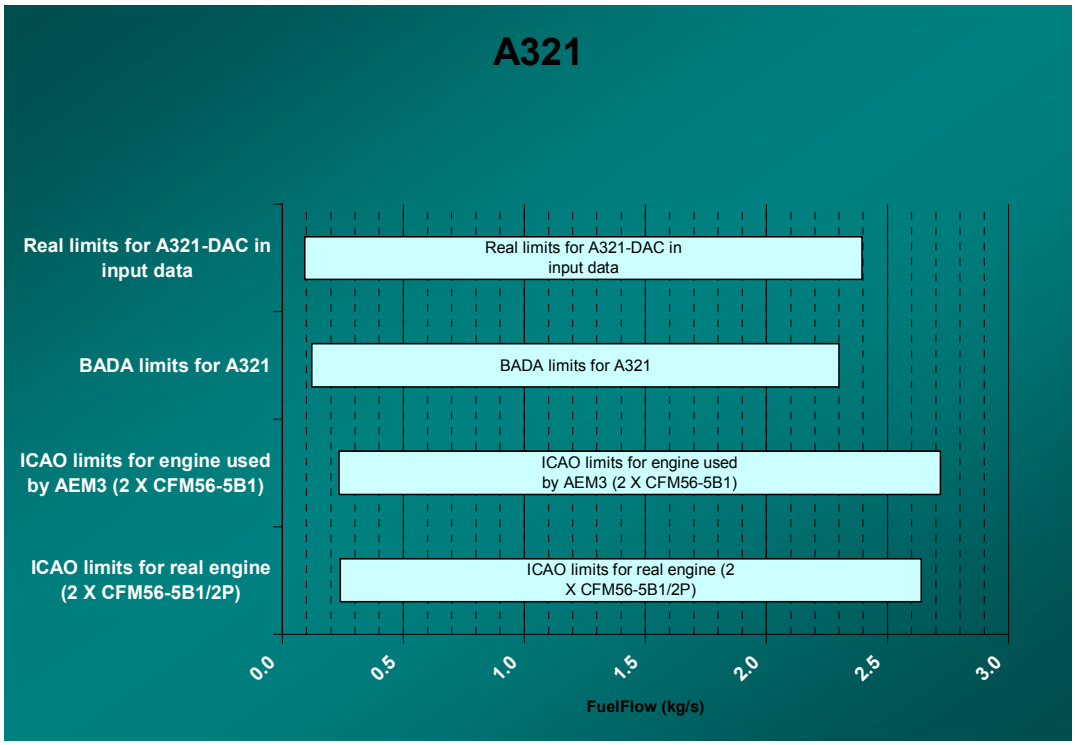


Figure 10: Fuel flow limits – A321

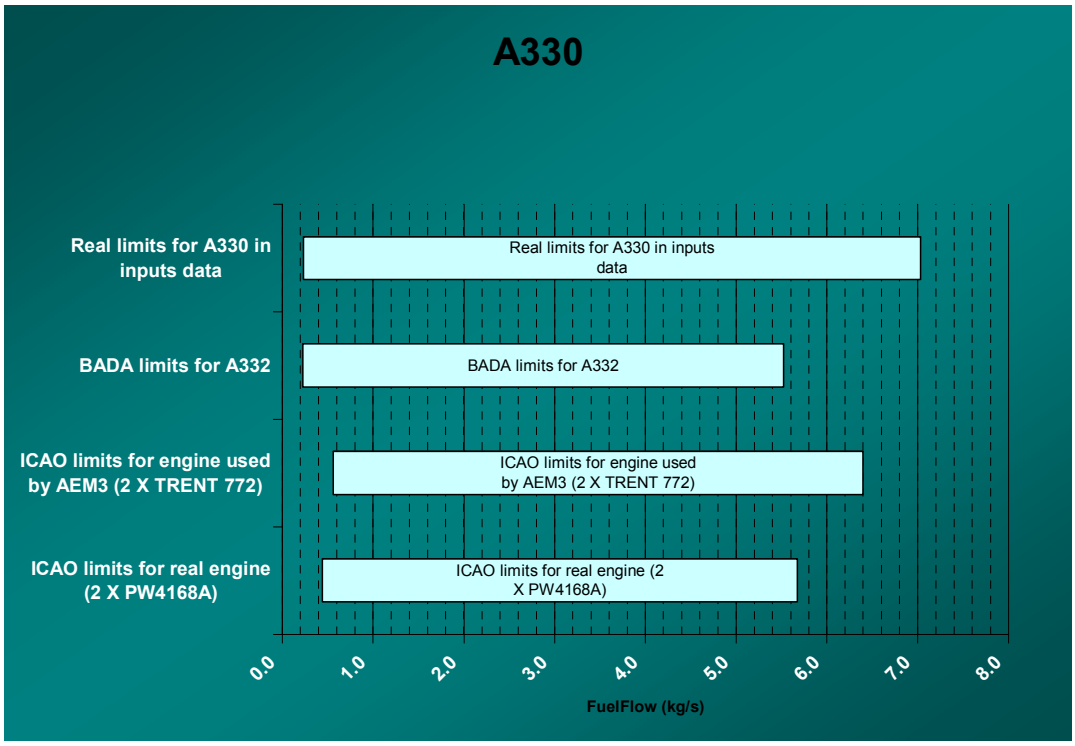


Figure 11: Fuel flow limits – A330

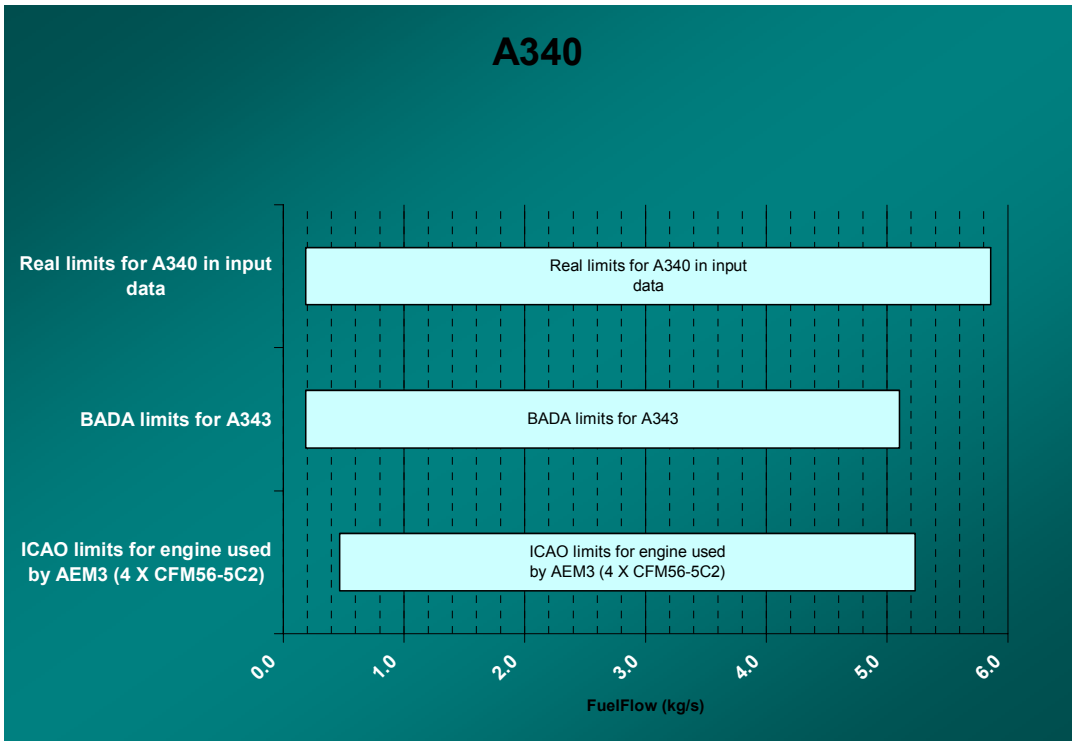


Figure 12: Fuel flow limits – A340

No “real” data were available for the emissions validation. Instead, AEM3 results were compared against results from other studies published by NASA and ANCAT.

CO_2, H_2O, S_20

The emissions for CO_2, H_2O and SO_x are directly proportional to the fuel burn, therefore any built-in error in the fuel burn estimates will propagate to these emissions.
The emissions coefficient representing the degree of proportionality between fuel burn and the above pollutants have been based on an in-depth literature review. There is only a slight variation for those coefficients in the different literature sources, and the values applied by AEM3 have been qualified as reasonable by different domain experts.

Pollutant	AEM3	Max	Min	Max %	Min %
CO_2	3.149	3.22	3.1	2.254684	-1.55605
H_2O	1.23	1.25	1.17	1.626016	-4.87805
SO_2	0.00084	0.0012	0.000267	42.85714	-68.2143

Table 33: Variation in published coefficients for fuel-proportional emissions (%)

Above table indicates the variation for these coefficients in the different literature sources as compared to the coefficients applied in AEM3. The variation indicates the same level of error which might be applied by those coefficients into the AEM3 results for CO_2, H_2O and SO_2.

NO_x, CO, HC

The estimation of the level of realism for the NO_x, CO and HC emissions estimated by AEM3 is based on information available from research projects performed by ANCAT and NASA, since real emission data for validation purpose is not available.
Most of the validation of emissions was made using a microscopic approach.

ANCAT

ANCAT inventories provide fuel, NO_x, CO and HC for many aircraft types based on the distance flown (translated into the notion of typical mission ranges). Calculation of emissions produced during LTO for ANCAT/EC2 is based on the *ICAO Engine Emissions Data Bank*. Estimation during the climb, cruise and descent phases is performed by the DLR NO_x estimation method detailed in 0. The fuel information required to create the emission inventory have been obtained using PIANO.
To achieve a fuller global coverage, the ANCAT data set is a combination of actual flight plan data from ATC sources as well as published sources like OAG Airline Guide, ABC Travel Guide and Aeroflot timetable. This data set is not as precise and accurate as the FDR validation data set, which introduces some uncertainty into the comparisons.
The ANCAT/EC1A inventory data sets have been released by the ANCAT/EC group of experts in April 1994 and the ANCAT/EC2 inventory data sets in August 1997.

NASA

The "Scheduled Civil Aircraft Emission Inventories for 1992" report from NASA 0 describes the development of a database of aircraft fuel burn and emissions from scheduled air traffic for each month of 1992. The inventories have been calculated using the Official Airline Guide (OAG) as the source of scheduled flight data. Flight scheduled data (number of departures for each city pair along with airplane and engine type) have been combined with performance and emissions data to calculate the fuel burn, emissions, and altitude along each route.

The Boeing Method 2 has been used to estimate emissions for non-LTO phases. Emission estimation for LTO phases have been performed with the *ICAO Engine Emissions Data Bank*.
Results for 1992 have been compared against a previous study dating back to 1990. The revised calculations show significant increase in the calculated hydrocarbon emissions. NASA states that this is due to the inclusion of more older aircraft/engines combinations in the performance analysis.
As NASA study is based on OAG data, flight profiles used for emissions estimation are theoretical and only based on aircraft performances and supposed flight levels. We expect to obtain differences in the results when compared against AEM3 results from FDR profiles.

NOx, CO and HC Distribution

The *NASA Scheduled Civil Aircraft Emission Inventories* for 1992 0 indicates that the internal distribution between the three above pollutants should vary between 72.5 and 90% for Oxides of Nitrogen, 25 and < 10% for Carbon Monoxide and <1 - 2.5% for Hydrocarbon, dependent on the mission length. The estimation is based on Boeing standard mission profiles, for a mission range between 750 and 5500 km (400 NM and 3000 NM) for a B757-200.

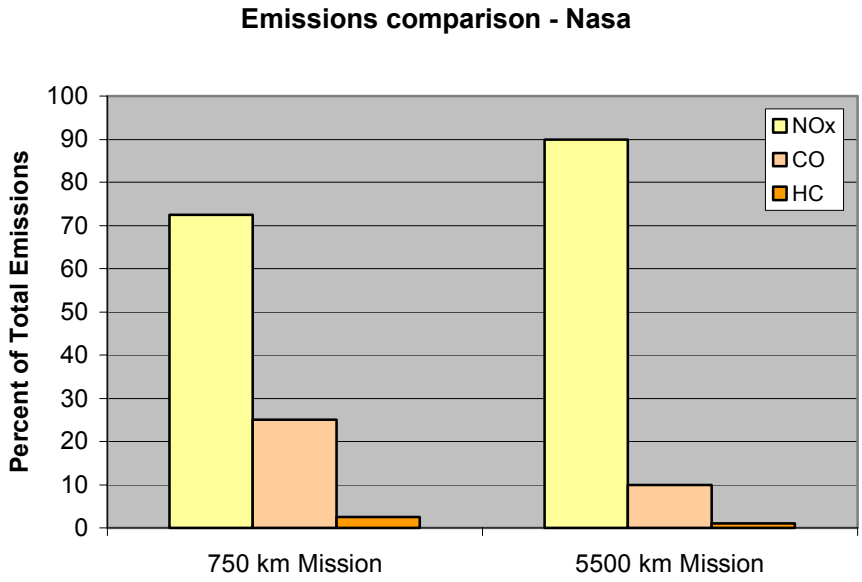


Figure 13: Emissions Comparison of 757-200 for a 750 km and 5500 km Mission 0

FDR data (HC & CO indicies limited)

The following table indicates emission distribution for FDR data depending on distance range.

Distance Range	Distance Range		Number of flights	AddAll			NoAdd		
	Between (km)	And (km)		% NO_x	% CO	% HC	% NO_x	% CO	% HC
Short	0	1000	2338	72.73	25.19	2.08	75.88	22.21	1.91
Medium	1000	5000	150	77.45	20.20	2.35	78.77	19.07	2.16
Long	5000	10000	1345	82.42	16.75	0.82	83.70	15.62	0.68

Table 34: Emission distribution for FDR data

Figure 14 provides the same information in a graphic.

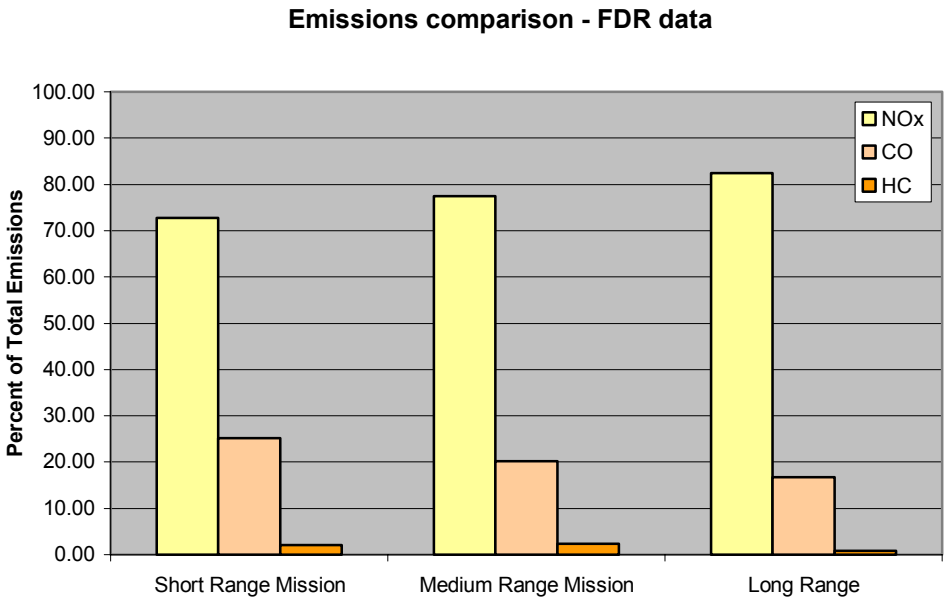


Figure 14: Comparison of Emissions Produced by AEM3 with FDR data

The main contributors to HC and CO emissions are low altitude phases and the descent phase, while almost all the NOx is emitted during climb and cruise phases (see paragraph "Emissions Along the Flight Profiles"). As a consequence when the flight's length grows, the influence of LTO cycles decreases.
We expect "Figure 14: Comparison of Emissions Produced by AEM3 with FDR data" to show a growth of NOx percentage and decrease of CO and HC percentages.
When looking at Table 34 and Figure 14, we note that this tendency is followed by the results. NO_x, CO and HC distribution follow perfectly the predictions of the *NASA Scheduled Civil Aircraft Emission Inventories* for 1992. NO_x varies between 72.73 and 83.70; CO between 15.62 and 25.19; and HC between 0.68 and 2.35 depending on mission range and profile completion.

Above results have been obtained by limiting the HC and CO emissions indicies for very low BADA fuel flows (lower than the ICAO documented idle limit) to the emission indicies documented by ICAO for idle.
A further break down by aircraft type (Table 35) has been done to eliminates the fact that in the data set different distances are often covered by different aircrafts.

ACType	Distance Range	Number of flights	AddAll			NoAdd		
			% NO_x	% CO	% HC	% NO_x	% CO	% HC
A319-DAC	Short	914	76.12	23.51	0.36	79.00	20.65	0.35
A320-DAC	Short	908	71.38	25.69	2.92	74.56	22.67	2.77
A320-SAC	Short	26	72.37	24.94	2.69	75.11	22.39	2.50
	Medium	107	72.14	24.53	3.33	72.49	24.15	3.36
A321-DAC	Short	475	70.24	26.73	3.03	73.65	23.66	2.68
A330	Short	13	78.50	19.98	1.52	80.84	17.82	1.33
	Long	1305	82.43	16.79	0.78	83.70	15.65	0.64
A340	Short	2	74.78	21.97	3.25	80.85	16.77	2.38
	Medium	43	80.21	17.95	1.84	81.99	16.47	1.54
	Long	40	82.34	16.16	1.50	83.59	15.12	1.29

Table 35: Emission distribution per ACType for FDR data

A320-SAC, A330 and A340 are used for different distance ranges. If A330 and A340 follow the expected tendency, A320-SAC does not. The key reasons are discussed below.
One reason why a shorter flight produces a higher NO_x percentage than a longer one with the same aircraft is that the flight profiles are not necessary comparable. Longer flights present a longer descent phase during which much more HC and CO is produced than during the shorter flights' descent. The percentage of HC and CO regarding the NO_x one's increases.
Another reason comes from the flight profiles themselves. Long legs from for example FL290 to FL285 are considered as descent phases. Fuel burn rate applied and consequently emission estimation are based on "descent" values. The real engine settings don't obviously correspond to a descent phase but to a cruise one. In this case, AEM3 indicates more HC and CO than it should. The same phenomenon appears for long unrealistic climb phase. In this case, more fuel burn and NO_x are indicated by AEM3 than are produced in reality.

> A way of solving this feature has to be studied. It might be either a correction of attitudes inside AEM3 or a special file preparation advise to indicate to AEM3 users before they perform any calculation with AEM3. However the difference between a realistic and an unrealistic climb/descent phase is easy to check manually but very difficult to perform without error through an automatic algorithm.

As explained in section "Flight Profile Analysis: Fuel Flow", fuel flows indicated by BADA are for some legs lower than idle fuel flow from *ICAO Engine Exhaust Emissions Data Bank*. This creates a high overestimation of HC and CO and influences the emission distribution.

These different phenomenon combined explain the fact that NO_x proportion may not always be higher for long haul flights.

SITA data (AddAll;HC & CO indicies extrapolated)

The emission analysis for the SITA data had been performed before the introduction in AEM3 of a limitation of HC and CO emission indices for very low fuel flows. Low fuel flow emission indicies are calculated by extrapolating the existing linear trend in the Log-Log Graph of the Boeing curvre fitting method below the ICAO idle fuel flow. As a result the HC and CO emissions are significantly higher. The emission distribution obtained for SITA data is the following:

Distance Range		Number of flights	Avg Of Distance KM	% NO_x	% CO	% HC
Between (km)	And (km)					
0	500	2717	374	60.65	34.79	4.55
500	1000	780	639	41.74	49.26	9.00
1000	1500	133	1217	48.20	44.16	7.65
1500	2000	81	1708	64.58	32.14	3.29
2000	5000	79	2638	68.63	28.73	2.64

Table 36: Emission distribution for SITA data

The results indicate that in reality the CO and HC emissions, based on lower fuel flows than documented in the ICAO Engine Exhaust Emission Data Bank, are significantly higher than estimated so far.

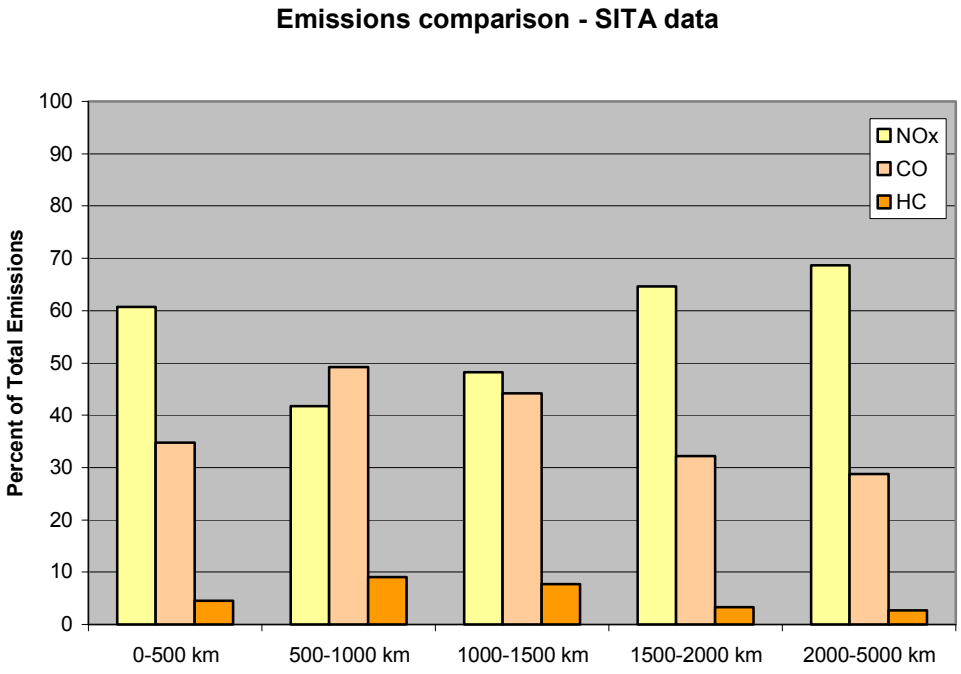


Figure 15: Comparison of emissions produced by AEM3 with SITA data

Figure 15 shows that the results for flights between 500-1000 and 1000-1500 km do not follow the expected trend of increasing Nox emissions and descreasing CO and HC emissions with increaseing mission distance. CO emissions become even dominant in the results for the flights between 500 and 1000 km.

The results indicate that the CO and HC emission estimation for low fuel flows requires a further serious discussion on domain expert level.

NOx Average Emission Indices from ANCAT and NASA

NASA and ANCAT researchers have analyzed the NO_x emission estimates for larger traffic inventories and calculated the amount of NO_x emissions in relation to the estimated amount of fuel burn. These calculated values are called Average NO_x Emission Indices (EINO).
This analysis lead to the following estimations for average NO_x Emissions Indices in g per kg fuel burn:

	ANCAT 1A	ANCAT 2	NASA	NASA
	1992	1992	1990	1992
horizontal resolution (°)	2.8 * 2.8	1 * 1	1 * 1	1 * 1
vertical resolution (km)	1	1	1	1
$EINO_x$ (g/kg)	16.8	13.7	10.9	11.1

Table 37: Published average $EINO_x$ (g/kg fuel) of reference projects 0

Source: Impact de la flotte aérienne sur l'environnement atmosphérique et le climat; Rapport no.40, Décembre 1997, Institut de France, Académie des sciences - Académie Nationale de l'air et de l'espace.
NASA results are based on Boeing Method 1 and Method 2.
ANCAT 1A results have been obtained using a thermo-dynamic NO_x emission model which has been replaced during ANCAT 2 by the DLR NO_x estimation method. The ANCAT/EC2 inventory in the base year 1991/1992 (published in 1998) estimates that the civil subsonic fleet average emissions index ($EINO_x$: g NO_x/kg fuel) is 13.7. This estimation is significantly lower than the previous ANCAT/EC1A study published in 1995 which indicated an average of 16.8 g NO_x/kg fuel. This difference is due to revisions to the movement data base and use of a different methodology for the prediction of NO_x at cruise altitudes.
A comparison by Rolls-Royce experts, using both the Boeing Method 2 and DLR NO_x emission method, indicates a difference of 3.6% with the DLR method giving the higher NO_x estimation.
The results published in this report are obtained through the application, within AEM3, of a modified version of Boeing Method 2. The modification compared to the original Boeing Method 2 covers a correction in the formula to correct for humidity at flight level.
A brief comparison during previous studies between DLR method, Boeing Method 2 and the EUROCONTROL modified Boeing Method 2 (EEC-BM2) indicates that the DLR method delivers 4.28% higher results than the Boeing Method 2 and 3.56% higher results than the EEC-BM2. This would lead us to expect that average Emission indices for NO_x for the FDR validation movement data should lie slightly higher than the most recent values published by NASA.
The following tables indicate the average NO_x emission indices in g per kg fuel obtained for the different scenarios under analysis.

ACType	Number of flights	EINO$_x$ AddAll	EINO$_x$ NoAdd
A319-DAC	921	14.31	15.23
A320-DAC	911	13.38	13.92
A320-SAC	133	11.58	11.73
A321-DAC	475	17.20	17.37
A330	1318	11.53	11.33
A340	87	14.81	14.92
Total	*3845*	*13.41*	*13.72*

Table 38: AEM3 estimated EINO$_x$ averages in g/kg fuel with FDR data

SITA data can be used in this section since AEM3 profile completion does not affect NO$_x$.

Aircraft	Number of flights	EINO$_x$
A306	193	16.31
A310	200	16.37
A319	418	13.93
A320	697	13.36
A321	504	17.71
A340	5	20.93
B733	942	11.81
B735	824	11.77
B742	6	16.66
B744	1	16.08
Total	***3790***	***13.54***

Table 39: AEM3 estimated EINO$_x$ averages in g/kg fuel with SITA data

Aircraft with fewer than 10 flights are not taken into account in the total.
The previous tables confirm perfectly the expectation, indicating the average NO$_x$ emission indices in g per kg fuel obtained for the different scenarios under analysis. The average EINO$_x$ over all validation data lies from **13.41 to 13.72 g/kg** fuel burn depending on options. These results are about 20.7 % to 23.5 % higher than NASA results from 1992, but 2.1 % lower or 0.1 % higher than ANCAT2 results.
These figures also show very clearly that average emission indices, especially for NO$_x$, are very sensitive and should be applied only very carefully. Any study using such average EINO$_x$ to calculate “backwards” absolute figures for NO$_x$ emissions should be considered with strong reservations.

Emissions Along the Flight Profiles

The following Table 40, Figure 16 and Figure 17 break down percentages of emissions produced per flight phase. They confirm the expected repartition of pollutants per flight phase. NO$_x$ is emitted mainly during climb and cruise phases, CO and HC during descent phase.

Attitude	AddAll			NoAdd		
	% NO_x	% CO	% HC	% NO_x	% CO	% HC
Climb	95.3	4.5	0.2	95.4	4.4	0.2
Cruise	86.2	13.5	0.3	86.2	13.5	0.3
Descent	17.6	76.4	6.1	19.9	73.9	6.2

Table 40: Pollutant distribution per flight phase (%)

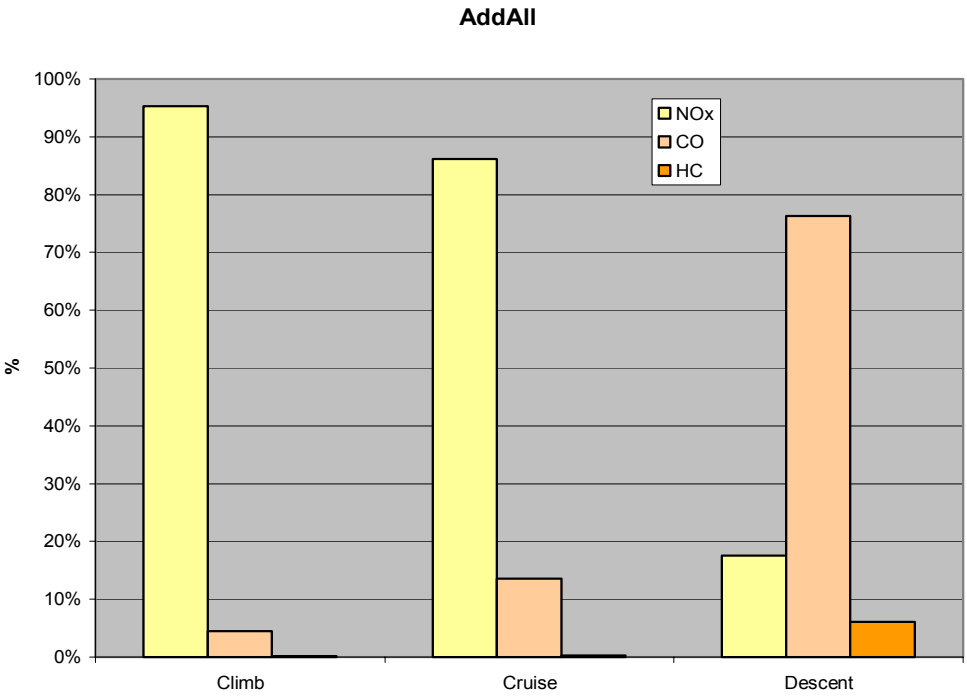


Figure 16: Pollutant distribution per phase - AddAll

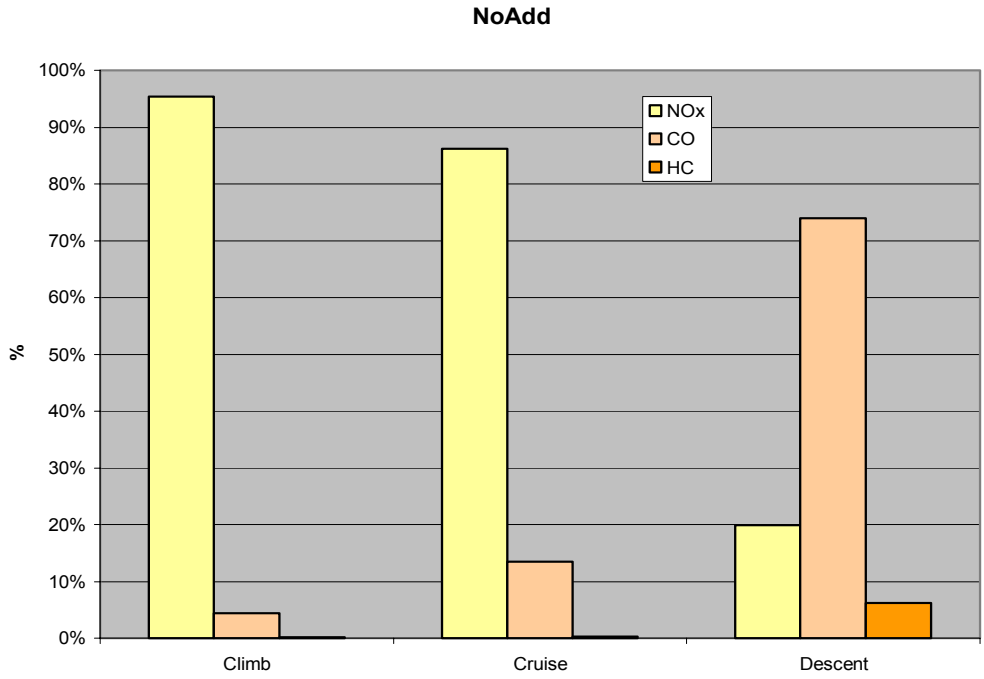


Figure 17: Pollutant distribution per phase - NoAdd

Figure 18 to Figure 20 show the evolution of NO_x, CO and HC emission indices. Three typical flights are plotted as done for fuel flow in section "Flight Profile Analysis: Fuel Flow". The flight profiles (FL versus time) are also plotted and refer to the secondary axis on the right.

$EINO_x$ is expected to be very low during taxi, increase during climb phase, remain high during cruise phase, and decrease during descent phase. On the other hand, EIHC and EICO are supposed be high during taxi and descent phase, where the combustion process is less complete.

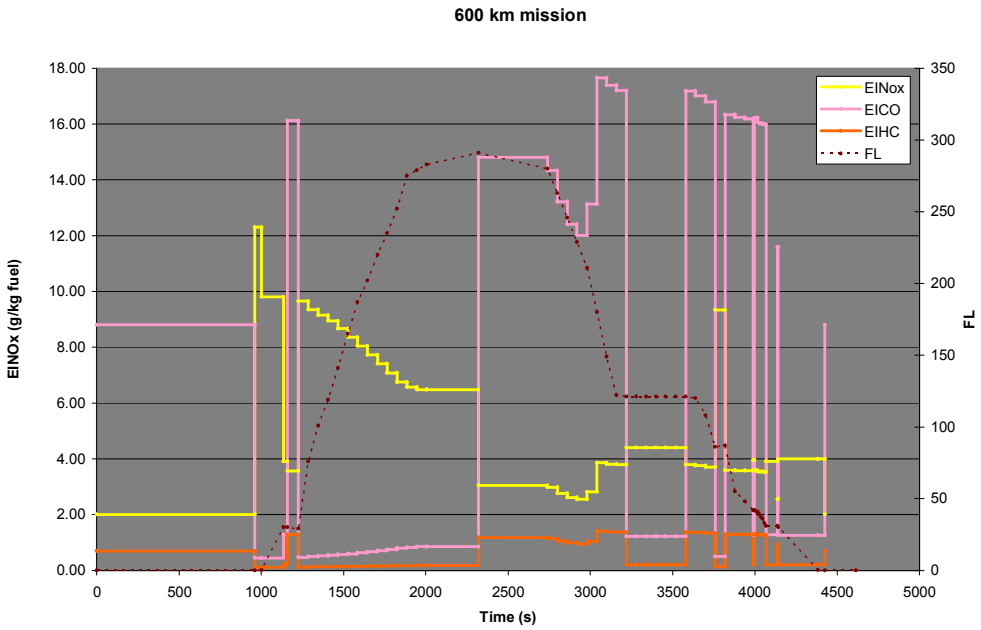


Figure 18: Evolution of NO_x, CO and HC emission indices along a 600 km mission

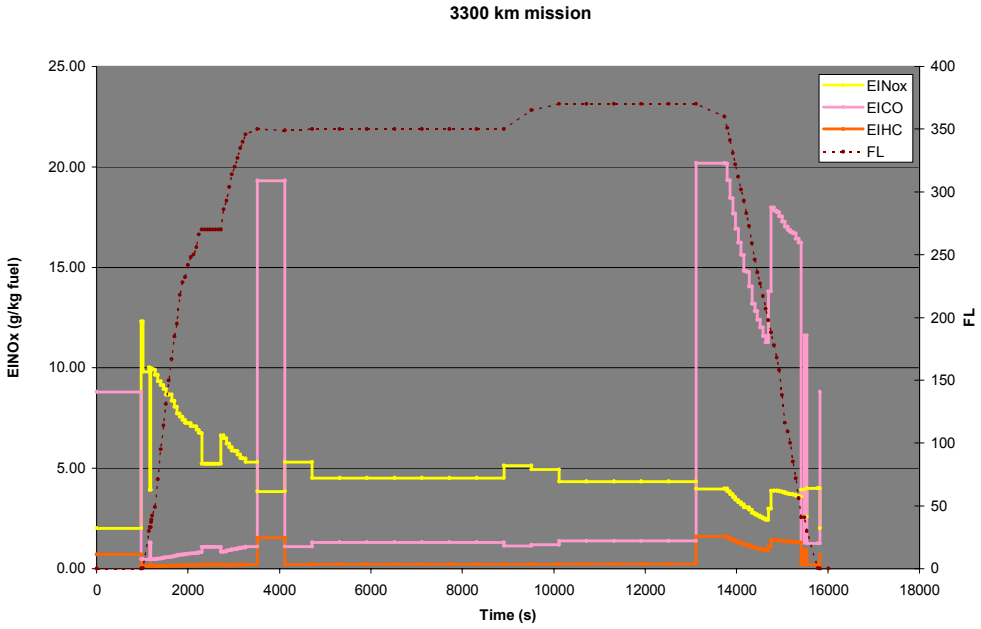


Figure 19: Evolution of NO_x, CO and HC emission indices along a 3300 km mission

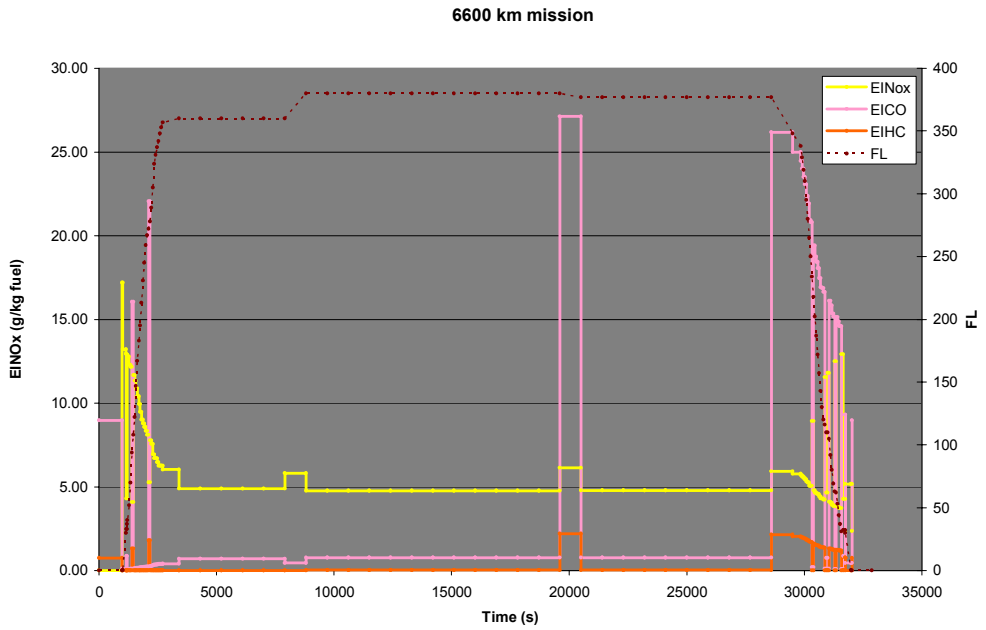


Figure 20: Evolution of NO_x, CO and HC emission indices along a 6600 km mission

The tendencies are verified in Figure 18 to Figure 20. The peaks are due to the same phenomenon as explained in section "Evolution of Fuel Flow".
The peaks due to short descent phases during the main cruise phase, if appearing during "long" legs, have a strong influence on results. Indeed the HC and CO emissions indices during these peaks are significantly high compared to cruise level of emission indices. They create a consequent overestimation of HC and CO emissions.
No attempt was made to quantify this overestimation, because it depends only on the input data, and especially the duration of legs.

VOC / TOG

The AEM3 VOC/TOG estimation approach follows a method developed and published by U.S. EPA.
Within this method, the VOC and TOG estimations are documented to be directly proportional to the quantity of HC. As a consequence, a potential error in HC estimation is propagated to VOC and TOG calculations. This underlines the importance to develop clear guidance material for low fuel flow emissions of HC and CO.
The verification of the reliability of the method developed by U.S. EPA is clearly outside the scope of this validation project on AEM3. No further verification of the documented relationships has been undertaken.

As any other model, the AEM3 calculations are subject to limitations. This chapter does not aim at drawing up a complete list of limitations. It focuses on some identified limitations due to different aspects.

Limitations due to the tool conception

No flight profile calculator tool
Despite the fact that AEM3 is able to complete (in a simplified way) incomplete flight profile information, it does not include the functionality of a complete flight profile calculator. This is a conceptual choice of the AEM3 developers, since flight profile calculator tools, due to the complexity of the domain, should not be incorporated in other models but be kept separate as a specific model appart.

No detailed geographical modelling of TMA operations (SIDs/STARs)
In the context of global or large scale emission studies usually the traffic samples do not include any detail about the aircraft operation at low altitudes or ground level at the airport or in the airport neighbourhood. Based on this input constraint, AEM3 has been designed to model the Airport related operations, e.g. TaxiOut, TaxiIn, TakeOff run, etc. purely as a function of the duration of those operations. Those operations are considered by AEM3 to take place at the airport latitude and longitude and the flight does not evolve geographically. This constraint has no significant relevance in the context of global emission studies, but would need to be addressed if AEM3 would be required to cover in futur local air quality issues in addition.

Single engine taxiing
AEM3 does currently not allow directly to model single engine taxiing. Nevertheless, this way to operate can be easyly included in the AEM3 estimations by some simple database querry manipulation of the AEM3 output for the airport, airlines or aircraft types concerned.

Nominal weight and weight evolution
Dependent on the actual TOW fuel burn rates and as a result emissions vary in real flight operations. The reduction of the aircraft weight along the flight profile as a function of the fuel already burnt, leads to reduced fuel burn rates as a function of mission duration.
AEM3 input data sources such as radar data, ATM flight plans, Real and Fast Time simulator traffic samples, usually do not contain any weight information.
BADA as the underlying source for fuel burn information provides such data based on a nominal and constant weight assumption per aircraft type.
A parametric approach would allow to address these two issues, although, seeing the currently high quality level of the AEM3 estimations, this might not be absolutely necessary in the context of global emission studies.

Aircraft/engine combination distribution
In its current version AEM3 allows only to associate one specifc engine type to each aircraft type, where in reality one aircraft type can be fitted with different engine types, e.g. an Airbus A320 can be powered by CFM56-5 and IAE V2500 engines.
A random association of the different possible engine types to the aircraft types appearing in the movement data set based on statistical engine distribution information could further improve the quality of the AEM3 results in the futur.

Airport-, Airline- or Aircraft dependent times in mode concept

The current concept of airport dependent mode times for TaxiIn and TaxiOut operations could be transfered and further improved to the modelling concept of this and other aspects, such as TakeOff times etc. to more realistically modell the LTO operations. Beside minor evolutions of the current AEM3 algorithm this possible improvement would require major effort to aquire the required underlying data.

Meteorological situation
One current limitation of AEM3 is the use of the ISO Standard Atmosphere data for the entire geographical area covered by the movements under analysis. This limitation can be mostly overcome already today when AEM3 runs are performed in the framework of the Toolset for Emission Analysis (TEA). TEA includes a detailed meteorological model allowing to produce pressure, temperature, and humidity information in form of a 4D grid. TEA does not yet take into account the wind situation.
As discussed in Appendix A, for each degree increase in temperature from the ISA standard atmosphere HC and CO emission indicies rice of about 1.4%, where the NOX EI decreases by about 0.7%. These figures give an indication of the error margin based on fact the meteorological situation is modelled using the ISO Standard Atmosphere.

A study tool
AEM3 has been designed to support aviation emission studies to test the environmental impact or benefit of modifications to the ATM system, e.g. implementation of RVSM, Free Flight etc.
It has not been designed to produce emission inventories automatically. Nevertheless, with the current PC version of AEM3 v1.5 emission inventories can be produced with some additional manual effort concerning the input and output data treatment.
This limitation should become obsolete with the availability of Batch-AEM in close future.

Limitations due to the underlying databases

The precision of calculations performed by AEM3 can not exceed the precision of the input data used for the calculation. Beside that, the quality of the underlying system databases (BADA, ICAO, etc.) are mainly influencing the quality of the AEM3 results.
The ICAO engine exhaust emission databank is a unique source of data, which holds engine certification test information for fuel flow and emissions. The information provided is based on 1-10 test of 1-10 engines. In most cases 3 tests have been performed with a single or two engines. From an statistical viewpoint this is insufficient to determine the potential variation of engine parameters, e.g. fuel flow, for a specific engine type. The use of this data in the context of emission analysis could lead to over or underestimations of emissions for specific engine types, where the potential margin for such over- or underestimation remains unclear.
BADA does not provide direct data for all aircraft types operated in the world. Data for about 89 aircraft types is directly available. Fuel burn for other aircrafts are estimated through a list of "equivalent aircrafts". During the use of AEM3 in several studies during the last 3 years the initial BADA equivalency list has been extended for aircraft types which did not appear on the initial list. Both, direct and equivalent models on the AEM3 aircraft list cover the european movements to a very hight extend (more than 99% of all flights; see ANNEX C).

Conclusion

Very effort intensive and mostly manual verifications have proven the correct implementation of the AEM3 design concept, algorithms and methods.
The following validation was mainly based on operational flight data recordings (FDR) acquired from one European airline for the project. This data gives a detailed picture of how the flight operation really was executed and how fuel burn evolved along flight operation.
About 3850 flights of such FDR data sets have been available to the validation project for Aircraft Types A319, A320, A321, A330 and A340.
In addition, operational flight plan (OFP) and fuel burn information in form of SITA messages from a different European airline was available to the validation project. Such data give a more or less detailed picture of how the flight was planned to be operated.
This plan data are of less granularity in terms of flight profile description and of less precision in terms of fuel burn information than FDR data. Nevertheless, since flight plan creation and fuel loading at airlines for an operational mission is based on several years statistical experience with the same aircraft type (in some cases even with the exactly identical aircraft and engines) it has been considered that such data can further support the validation project for AEMIII v1.5.
About 3800 OFP data sets including fuel burn planning for the Aircraft Types A300-600, A310, A319, A320, A321, A340, B737-300, B737-500, B747-200, B747-400 and MD-11, have been available to the AEMIII v1.5 validation project.
BADA provides to AEM3 underlying aircraft fuel burn information. BADA data is based on and produced with airframe manufactures proprietary data and modelling tools and is well understood in terms of error margins.
Validation was planned to be performed for each Aircraft Type individually for the complete flight profile and with a focus on LTO operations. (Taxi Out, Take Off, Climb Out, Climb, Cruise, Descent, Approach, Landing, Taxi In). Due to data incompleteness the focus was limited to the departure parts of the LTO cycle, e.g. TaxiOut, TakeOff, Climb Out.
For the 21 departure airports appearing in the FDR data, AEM3 v1.5 overestimated TaxiOut duration in average by 62 %. The underlying AEM3 TaxiOut information against FDR TaxiOut durations was compared was intially extracted from 1998 OFP data. It should be kept in mind , that this oberestimation is relevant to and based on TaxiOut information for 1 airline, 6 aircraft types and missions departing at 21 airports of international significance (6 European, 4 US, 7 Middle East & 4 Asian).
Nevertheless, the validation indicates the AEM3 TaxiOut default duration to be significantly lower than the TaxiOut durations for the 19 airports included in the SITA data. Compared to that, the ICAO value for TaxiOut duration appears to be much too high for those 19 airports. Nevertheless, as will be explained later in more detail, the AEM3 default value is an average figure, based on airport TaxiOut information (operational & declared) of more than 3000 airports. This seems to assure that in average this value is close to reality. On the otherhand, this comparison shows that the ICAO duration for TaxiOut operation is much too high compared to real aircraft operation.
The results of AEM3 v1.5 indicate that its concept to try to differentiate TaxiOut times on a Airport per Airport base and not to work from the beginning with a global average for all airports, goes into the right direction. This AEM3 concept is as well consistant with the findings and requirements expressed by the AEROCERT project.
The quality of the AEM3 fuel burn and emission estimation on TaxiOut operations (dito for TaxiIn) relies mainly on the realism of underlying taxi duration data.
AEM3 v1.5 will be updated before delivery to users with the up-to-date TaxiOut information for the 21 airports appearing in the FDR data samples, assuring that the duration error will be close to zero.

To further improve AEM3 TaxiOut fuel burn and emissions estimations, the definition of a regular update process for Taxi data is required. It is currently investigated if such updates could be based on taxi information extracted out of the EUROCONTROL CODA system.
This validation projects indicates that AEM3 overestimates for the 3850 FDR missions TakeOff operation duration by 8 % (average TakeOff duration of FDR data of 39 seconds). AEM3 TakeOff duration is based on the ICAO Exhaust Engine certification duration for the TakeOff mode (equal 42 seconds). The resulting fuel over estimation reads 11 %.
To improve the AEM3 estimation quality for TakeOff operations, it is currently under discussion if TakeOff duration should be implemented at least as a function of the aircraft type. The short duration of the TakeOff run, its little contribution in terms of fuel burn and emissions over the entire mission and the effort required to further reduce the error level already obtained in AEM3 would need to be put in relation with the potential for improvement. Where this might be questionable worth the effort in the context of Global Emission analysis, the increasing public interest in Local Air Quality issues might nevertheless require to address this issue in the close future.
Duration for ClimbOut operations is indicated to be overestimated by 64 % (average ClimbOut duration: 80 seconds). As for TakeOff, AEM3 ClimbOut duration is based on the ICAO Exhaust Engine certification value for the corresponding mode (132 seconds for climb out). Fuel is thus overestimated by 51 % for this phase of the flight.
It seems not realistic that it would be possible to create a database which holds ClimbOut duration as at least a function of the departure airport and aircraft type on a global level. To achieve improvement it seems to be the most pragmatic approach to aim to agree on a new “standard” average duration for ClimbOut operations on an international level. This should be base on the analysis of a large number of up-to-date FDR datasets, considered to be representative for European or better Global air traffic movements. Such activity could, dependent on resource and data availability, become a future part of the GAES-Move project (follow-up project of the EUROCONTROL Movement database contribution to the AERO2K project).
The time for combined TakeOff and Climb-Out operations (39 + 80 = 119 seconds) extracted from the FDR data is well below (42 + 132 = 174 seconds = 46 %) AEM3 (and ICAO certification) times. This confirms similar findings during the AEROCERT project which where based on significantly smaller number of FDR flight profiles than the AEM3 validation project.
AEM3 uses as well the ICAO Engine Exhaust certification time for the approach mode (240 sec), to define a model approach duration. The compare to the information extracted out of the FDR data sets indicate an overestimation of the approach duration by AEM3 (and ICAO) of about 4 %. This result is in contradiction with findings of the AEROCERT project, which indicates the ICAO reference time to be too low (12.5 – 46.4 %) compared to real operations. However, the overestimation of 89 % of the fuel burn during approach seems to indicate that the certification fuel flow figures from ICAO Engine Exhaust Emissions Data Bank are much higher than in messured in day to day aircraft operations.
Based on the current validation project it does not seem to be an urgent issue to modify the system default data for approach. It is planned nevertheless to analyse further airline FDR data dependent on availability as well for this aspect.
Despite the partly big error margins for the LTO operations (of relative short duration), the overall fuel error for complete missions is +1 %. Regarding an error on duration of +2 % due to flight completion, the visible fuel error excluding duration error is an under estimation of -1 %.
If no flight profile completion is performed by AEM3, the duration error is reduced to 0 and the fuel is under estimated by in average 3 %.

This is an extremly positive result for AEM3, which goes significantly below the acceptance limits as defined by ICAO/CAEP6.IP5 to be for the difference between measured and calculated fuel flow and directly proportional emissions within ±10%.
These very positive results are visualised for all 3850 FDR flights available to this validation project in below figure.

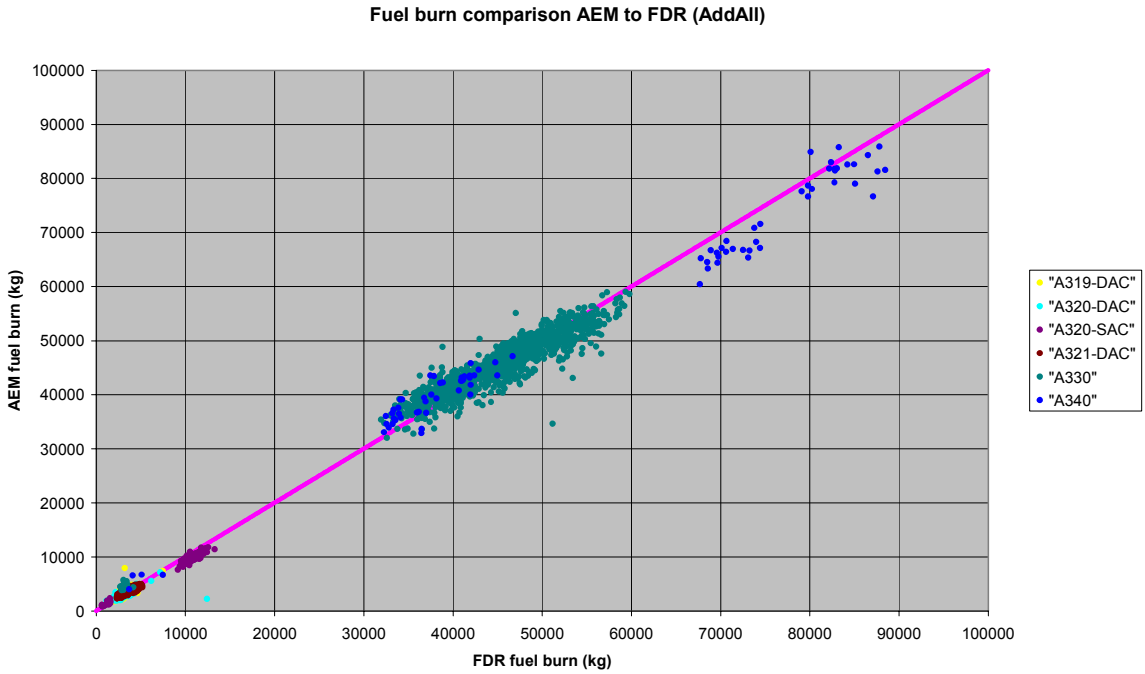


Figure 21: The AEM3 fuel burn vs. operational fuel burn for 3850 flights

The validation of AEM3 highlights significant differences for high and as well low thrust fuel flows compared to fuel flows documented in the ICAO Engine Exhaust Emissions Databank. This is a fundamental issue which requires further discussions with domain experts, since this would lead to wrong fuel burn and emission estimations of projects which purely rely on the ICAO fuel flows.
Since neither FDR information nor Flight plan data contain information on emissions along the flight execution the approach for emission validation inside this project is mainly based on comparison of AEMIII emission estimations against information published by different other reference projects in the domain, e.g. NASA, ANCAT etc.
AEM3 results are in accordance with the expectation.
The distribution of NO_x, CO and HC correspond to ranges published by NASA, if low fuel flow emission inidicies are limited to the 7% EIs documented in the ICAO Exhaust Engine Emissions Databank. At the same time NO_x average emission indices is about 13.5 g/gk fuel, which is very close to the published ANCAT findings.
If the emission indicies for very low fuel flows are not limited to the 7% limits, but extrapolated below this limit, significantly higher CO and HC emissions are estimated by AEM3 for a typical mission. Also this is one of the unexpected results of the AEM3 validation exercise it is considered that the results obtained in this way are closer to reality. Although the problem is known by ICAO/CAEP/6-IP5, no clear guidance material is available so far.
As a result of this validation exercise it can be concluded that the fundamental approach implemented within AEM3 v1.5 is leading to results with a very high level of realism. Fuel

burn calculations, based on BADA fuel flows are very close to real life quantities. Consequently, the same can be concluded for the fuel burn proportional pollutants, e.g. H_20, SO_x and CO_2. NOx results align with estimations of earlier domain expert projects and are based on a variation of the the widely regonised and accepted BM2 method, BM2-EEC modified.
VOC and TOG estimation rely equally on the accepted approach suggested by U.S. EPA.
CO and HC estimations would require for a future version of AEM3 clear guidance material how to estimate
below 7% thrust EIs for those two pollutants. The issue is suggested for dicussion on domain expert level.
Further activities should focuss on improvements of the underlying data sets holding most realistic operational LTO mode durations as a function of the used airport and/or aircraft type
Additional validation against FDR data from more airlines covering additional aircraft types is envisaged, where this depends mainly on the airlines readiness to support such validation activity with operational data.

References

Groupement des Industries Françaises Aéronautiques et Spatiales. Groupe de Travail. Environnement, Document de Synthèse. 11.04.2000.

The 8-States Free Route Airspace Project. FREE ROUTE AIRSPACE CONCEPT, Issue 1.3, 1 April 1999, doc. EUROCONTROL

AVIATION AND THE GLOBAL ATMOSPHERE, Intergovernmental Panel on Climate Change, 1999.

Klaus Gierens and Susanne Marquat, Regions that are conditioned for Contrail Formation, DLR, 2001.

Lee, D.S., I. Koehler, E.Grobler, F.Rohrer, R. Sausen, L.Gallardo-Klenner, J.g.J. Olivier, F.J. Dentener, A.F. Bouwam: Estimations of global NO_x emissions and their uncertainties" Atmos.Env.,31, 1735-1749, 1997.

WMO, 1995 WMO (World Meteorological Organisation): "Scientific assessment of ozone depletion: 1994", global ozone research and monitoring project, Report No.34, WMO, Geneva, 1995.

Koehler and. al, 1997: Koehler, I., R.Sausen, R.Reinberger: "Contributions of aircraft emissions to the atmospheric NO_x content" Atmos. Env., 31, 1801-1818, 1997

Brasseur and. al., 1998: Brasseur, G.P., R.A. Cox, D. Hauglustaine, I.Isaksen, J. Lelieveld, D.H. Lister, R.Sausen, U. Schumann, A. Wahner, P. Wiesen: "European scientific assessment of the atmospheric effects of aircraft emissions", Atmos. Env., 32, 1998

EUROCONTROL, FREE ROUTE AIRSPACE PROJECT, Fast Time Simulation Report. Phase 1, AOM/Z/FR, REF: 00.70.05, Edition: V1.4, Edition Date: 07 November 2000.

EUROCONTROL EXPERIMENTAL CENTRE, Eight-States Free Route Airspace Project Large Scale Real Time Simulation South Scenario, EEC. Report No.365, Project AOM-Z-FR, May 2001.

Scheduled Civil Aircraft Emission Inventories for 1992: Database Development and Analysis; April 1996; NASA LRC; Contractor Report 4700; Steven L. Baughcum, Terrance G. Tritz, Stephen C. Henderson, David C. Picket)

Impact de la flotte aérienne sur l'environnement atmosphérique et le climat; Rapport no.40, Décembre 1997, Institut de France, Académie des sciences – Académie Nationale de l'air et de l'espace

ICAO Engine Exhaust Emissions Data Bank ; ICAO ; Doc 9646-AN/943 ; First Edition – 1995 ; Internet Issue 1(3/10/1998) ; Internet Issue2(8/2/99).

Emission Indices – State of the Art; Literature Review; EUROCONTROL Experimental Centre; BU Environmental Studies; A.Celikel ; 1999 ; unpublished internal paper.

ANCAT/EC2: Global Aircraft Emissions Inventories for 1991/92 and 2015 – Report by the ECAC/ANCAT and EC working group – Editor R. M. Gardner

JP airline-fleets international Aviation Database – BUCHair UK ltd

ATS route record file extracted from The Digital Aeronautical Flight Information file (DAFIF) produced by The National Imagery and Mapping Agency (NIMA) of the United States Department of Defense (DOD) . http://164.214.2.62/products/digitalaero/dafifindex.cfm

"Aircraft emissions and the environment COx SOx HOx & NOx" – Leonie J Acher

AEMIII User Guide – Eurocontrol Experimental Centre – James Smith

Part of the EC Fifth Framework Programme project. Work Package 2--Construction of an Air traffic movements database - EUROCONTROL (EEC).

Documentation for the 1996 Base Year national toxics inventory for aircraft sources; Prepared by Eastern Research Group for U.S. EPA, Emission Factor and Inventory Group; June 2000.

For more information about the
EEC Society, Environment and Economy Research Area
please contact:

Ted Elliff
SEE Research Area Manager,
EUROCONTROL Experimental Centre
BP15, Centre de Bois des Bordes
91222 BRETIGNY SUR ORGE CEDEX
France

Tel: +33 1 69 88 73 36
Fax: +33 1 69 88 78 90
E-Mail: ted.elliff@eurocontrol.int

. ..