

Procedure for the Calculation of Aircraft Emissions

RATIONALE

This Aerospace Information Report (AIR) describes procedures for calculating emissions resulting from operations of jet and turboprop aircraft through all modes of operation. The procedures assume that reference emissions and performance data are available for each airplane involved. The fundamental element of the procedures is a method for deriving emissions indices for an airplane when performing any specified operation for a segment of a flight. The principal purpose of using the procedures is to assist model developers in calculating aircraft emissions in a consistent and accurate manner that can be used to address various environmental assessments including those related to policy decisions and regulatory requirements.

Rather than presenting one method, many viable methods are presented for both emissions and aircraft performance modeling with descriptions of the uncertainties involved. As a loose guide to the user, the methods are also ordered such that the most accurate methods are presented first in each section based on current understanding. This document is intended to be updated periodically. Hence, the methodology descriptions and uncertainty assessments will be modified accordingly as the various methods evolve and new information becomes available.

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1. SCOPE

This AIR describes procedures for calculating emissions resulting from the main engines of commercial jet and turboprop aircraft through all modes of operation for all segments of a flight. Piston engine aircraft emissions are not included in this AIR. Some information about piston engine aircraft emissions can be found in FOCA 2007. The principal purpose of the procedures is to assist model developers in calculating aircraft emissions in a consistent and accurate manner that can be used to address various environmental assessments including those related to policy decisions and regulatory requirements.

The pollutants considered in this document are:

- Nitrogen Oxides (NO_x)
- Carbon Monoxide (CO)
- Total unburned Hydrocarbons (THC)
- Carbon Dioxide (CO₂)
- Water (H₂O)
- Sulfur Oxides (SO_x)
- Volatile Organic Compounds (VOC)
- Methane (CH₄)
- Non-Methane Hydrocarbons (NMHC)
- Non-Methane Volatile Organic Compounds (NMVOC)
- Nitrous Oxide (N₂O)
- Particulate Matter (PM_{2.5} and PM₁₀)

As indicated above, hazardous air pollutants (HAPs) are not individually accounted for; many of these are simply included as part of THC. Also, trace metals are not included other than those that may already be accounted for as part of PM emissions. Since the scope is limited to aircraft engine emissions only, emissions from Ground Service Equipment (GSE), roadway vehicles, power plants, training fires, etc., are not included within this document. Although Auxilliary Power Units (APU), brakes, and tires are also part of the aircraft, their emissions (e.g., tire wear) are not within the scope of this document.

The methods are based on aircraft performance and emissions modeling. This means that only the pollutants exiting the exhaust of an engine are considered. Any atmospheric effects including those that occur in the near-field (e.g., exhaust plume) and the subsequent atmospheric dispersion are not modeled. The exception to this is in the computation of PM emissions.

In meeting the needs of modelers who may have varying fidelity requirements for both emissions and aircraft performance modeling, this document does not try to promote a single database and methodology. Therefore, several methods have been included in this document as indicated below with the emissions methods categorized by pollutants:

- Emissions Modeling Methods
 - NO_x, CO, and THC
 - P3T3
 - Boeing Fuel Flow Method 2 (BFFM2)
 - Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR) Method
 - International Civil Aviation Organization (ICAO) Reference Method
 - CO₂, H₂O, and SO_x
 - Fuel Composition Method (FCM)
 - VOC, NMVOC, CH₄ and NMTHC
 - Derivative Factor Method (DFM)
 - N₂O
 - Approximate Factor Method (AFM)
 - PM_{2.5} and PM₁₀
 - First Order Approximation (FOA)

- Aircraft Performance Methods
 - Aircraft performance data from flight data recorders
 - Manufacturer aircraft performance models
 - SAE AIR 1845 combined with Eurocontrol's Base of Aircraft Data (BADA)
 - Eurocontrol's BADA
 - Other aircraft performance models such as the Project Interactive Analysis and Optimisation (PIANO) tool

Both of these sets of emissions and aircraft performance methods are listed in the order in which they are presented in this document. And as previously indicated, the order generally denotes the level of accuracy where the first method in each section represents the most accurate method based on current understanding. The exceptions to this are:

Emissions Methods

- BFFM2
- DLR

Aircraft Performance

- SAE 1845 + BADA
- BADA

The ordering of these methods are arbitrary since they are considered comparable (e.g., BFFM2 is comparable to DLR). One other possible exception is the last listing under aircraft performance methods ("Other aircraft performance models"). The data from these other sources may be more accurate, comparable, or less accurate than the previously mentioned methods. This last category was added to include all other methods that were not based on manufacturer, SAE 1845, and BADA models.

In order to provide a better understanding of the relative condition of these methods, they have been defined into development status (i.e., "mature" or "developing") and fidelity (i.e., "simple," "intermediate," or "advanced") categories as presented in Table 1.

TABLE 1 - CATEGORIZATIONS OF METHODS

Category	Variable	Mature			Developing		
		Simple	Intermediate	Advanced	Simple	Intermediate	Advanced
Pollutant	NO _x	ICAO	BFFM2 DLR	P3T3			
	THC	ICAO	BFFM2 DLR	P3T3			
	CO	ICAO	BFFM2 DLR	P3T3			
	CO ₂	FCM					
	H ₂ O	FCM					
	SO _x	FCM					
	CH ₄				DFM		
	NMHC				DFM		
	VOC				DFM		
	NMVOG				DFM		
	N ₂ O				AFM		
	PM _{2.5}					FOA	
	PM10					FOA	
Aircraft Performance	Fuel Flow	ICAO		MM		SAEBADA	FDR
	Duration (mode or segment)	ICAO		MM		SAEBADA	FDR

Definitions of acronyms in the table:

- ICAO = ICAO Reference Method
- FCM = Fuel Composition Method
- DFM = Derivative Factor Method
- AFM = Approximate Factor Method
- BFFM2 = Boeing Fuel Flow Method 2
- DLR = DLR Method
- P3T3 = P3T3 Method
- FOA = First Order Approximation
- FDR = Flight Data Recorder
- MM = Manufacturer Models
- SAEBADA = Society of Automotive Engineers 1845 + Base of Aircraft Data

The “other” aircraft model category was not included in Table 1 since it is understood that it can be listed in any of the categories depending on which method/model is employed. The definitions for each of the categories are as follows:

Simple: This category represents the lowest complexity in terms of data requirements and computational procedures. The results generated from methods within this category are also considered to be the least accurate.

Intermediate: This category represents a middle-tier complexity in terms of data requirements and computational procedures. The results generated from methods within this category are also considered to be of middle-tier.

Advanced: This category represents the highest complexity in terms of data requirements and procedures. The results generated from methods within this category are also considered to be the most accurate.

Mature: Methods within this category are considered to be well-established. They have been used extensively in past studies and may have been validated to a certain extent.

Developing: Methods within this category are not considered to be well-established. The methods are still being assessed and are considered to be evolving.

In modeling aircraft performance and emissions, the main focus is on a single flight. This includes the complete operation and movement of the aircraft from gate-to-gate:

- Main engine start-up
- Ground taxi-out and delay activities
- Takeoff: Runway roll
- Takeoff: Initial ascent
- Climbout
- En route/cruise
- Airborne delay activities
- Approach
- Landing roll
- Thrust reverser
- Ground taxi-in and delay activities
- Engine shut-down

For modeling purposes, these modes can generally be simplified so that they are equated to one of the four LTO modes. Depending on the method, the actual modeling of the gate-to-gate movement may involve a segment-by-segment approach where results can be integrated to obtain totals by mode and flight. Currently, the AIR does not address emissions during engine start-up and shut-down activities. Also, thrust reverse operations are not directly covered in this AIR.

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The following publications for a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of the other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

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3. INTRODUCTION

Aircraft emissions refer to the release of pollutants (gaseous or particulate matter) into the atmosphere during an operation(s) of an aircraft. The factors affecting emissions are engine characteristics, aircraft performance characteristics, operations of the aircraft and engine, and atmospheric considerations. Each of these factors must be taken into account in properly evaluating the emissions of each pollutant as well as understanding the tradeoffs between pollutants.

Taking these factors into account, this Aerospace Information Report (AIR) provides guidance to promote the consistent and accurate modeling of aircraft emissions. All of the methods described in this document are existing methods; no new methodologies are specified. The AIR improves upon existing documentation for these methods by providing detailed, step-by-step descriptions and example calculations that clearly illustrate the correct understanding of these methods that were previously left to interpretation.

3.1 Overview of Effects on the Atmosphere

Aircraft emissions are of concern due to their impact on local air quality near the vicinity of airports and climate change. This concern has led to regulations that govern emissions during the Landing and Takeoff (LTO) cycle to address the local air quality issue. In recent years, the concern regarding aviation's contribution to climate change has increased in intensity. According to the Intergovernmental Panel on Climate Change (IPCC) report on "Aviation and the Global Atmosphere," aircraft in 1992 contributed about 3.5% of the radiative forcing by all anthropogenic activities associated with climate change (IPCC 1999). Recent long-term projection scenarios for the next fifty years have shown that aviation's share of fossil fuel consumption is likely to increase significantly.

The effect aircraft engine emissions have on the atmosphere depends on the type of emission, the altitude at which it is emitted, and its concentration. There are three atmospheric zones of concern: ground level, troposphere, and stratosphere.

The photo-chemical cycling of the oxides of nitrogen ($\text{NO}_x = \text{NO} + \text{NO}_2$) generates ozone (O_3). The production rate of O_3 is increased in the presence of biogenic (natural) or anthropogenic (man-made) hydrocarbons. The production of ozone in the presence of anthropogenic emissions is commonly called "smog" chemistry. The hydrocarbon emissions from aviation are frequently called total unburned hydrocarbons (THC). Ground level O_3 , THC, and smoke have direct health impacts such as irritating the eyes and respiratory tract. Carbon monoxide (CO) is considered very toxic and in low concentrations affects visual acuity and psychomotor performance. Smoke is also a visual nuisance and causes soiling of plants and buildings. Largely because of these concerns, the International Civil Aviation Organization (ICAO) has established standards that control the amount of NO_x , CO, THC and smoke that can be emitted during the LTO cycle which addresses emissions from ground level to 3000 feet. The ICAO LTO standards are reviewed periodically, and if warranted, for example as a result of advances in emissions reduction technology, the standards are revised to ensure manufacturers employ best available technology into their new products. Present regulations are primarily aimed at controlling emissions during the LTO cycle, but increasing attention has been directed towards considering other phases of flight.

In the atmosphere, the average temperature profile exhibits decreasing temperature with increasing altitude up to a characteristic altitude where the temperature trend slows and then reverses. The region where the slow reversal of temperature trend swings from negative to positive with increasing altitude is called the tropopause. The troposphere refers to the region of the atmosphere below the tropopause. In the troposphere, the negative temperature trend results in convective vertical mixing and large synoptic scale air motion. The tropopause varies from 11 miles (58,000 ft) at the equator to 6 miles (33,000 ft) at the poles. Aircraft powered by older products such as JT8D engines typically cruise at 33,000 – 35,000 ft, and fly almost entirely within this region. Aircraft powered by newer generation engines such as the GE90, RR TRENT and PW4000 typically fly up to 43,000 ft and spend a major portion of their flight in the upper bounds of the troposphere and in some cases above it. Consequently, the impact of aircraft engine emissions in this region is of particular concern. Whereas aircraft emissions in the vicinity of airports are primarily a health concern, emissions in the troposphere become a climate change issue.

Climate change projections are evaluated by calculating changes in the radiative balance, or how the composition of the atmosphere affects incoming sunlight and outgoing infrared. In this context, the changes in the atmosphere induced by the effects of aviation emissions can be long-term (e.g. CO_2) or short-term (e.g. contrail formation). The change in radiative forcing due to the emissions of CO_2 are relatively well understood. The effects of other emissions, however are currently not as clear. In the troposphere, the emissions of NO_x result in photochemical O_3 production, which is also a greenhouse gas. By influencing the balance of radical cycling, however, NO_x reduces atmospheric concentrations of another greenhouse gas, methane (CH_4). The impact of NO_x emissions has both positive and negative impact on the radiative balance. When injected in upper elevations of the troposphere the emissions of water vapor increase contrails and cirrus cloud coverage. The radiative forcing for cirrus clouds lead to a net increase in warming.

In the stratosphere, the temperature remains constant with altitude and there is no significant fluid motion and mixing. In this region, sunlight breaks O_3 into atomic oxygen and diatomic oxygen. NO_x chemically combines with atomic oxygen to catalytically deplete ozone. These reactions have prompted the large amount of research activity on ultra low NO_x combustors for aircraft designed to fly in this region. IPCC suggests that ozone depletion from subsonic aircraft is negligible due to the previously described O_3 -forming mechanism (IPCC 1999). Hence, O_3 depletion from subsonic aircraft is currently not an issue

3.2 Document Structure

In general, this AIR provides guidance on modeling emissions mostly based on the best publicly available data and methods. However, since there are various competing methods with varying data requirements and varying uses by modelers, no attempt was made to put forth one single method or only publicly available methods. That is, methods/data were not excluded based on level of accuracy. Rather, each of the predominant methods is described in detail with uncertainty qualifiers to provide modelers with a sense of each method's fidelity. The understanding here is that different methods may be appropriate for different modeling needs. However, in presenting these methods, a tiered approach based on a general sense of accuracy was used. This provides modelers with a guideline where they should consider using the most accurate method first if their resources allow (e.g., they can get access to the appropriate data). If not, they can move down the list with decreasing accuracy until they come to a method that suits their resources and accuracy requirements.

In addition to emissions, the document also provides methodologies to model aircraft performance. This mirrors the current contents of AIR1845 which provides guidance on modeling noise from aircraft. However, unlike AIR1845, more than one performance methodology is presented. And similar to the emissions sections, the performance methods are also presented in a tiered fashion allowing the modelers to determine the method that best suits their needs.

Section 2 presents an overview of the purpose and scope of this document including pollutant and methodology coverage. Section 3 provides a discussion on the key engine and aircraft characteristics that affect emissions, and also describes the reference conditions commonly used by the various computational methods. Section 4 contains the main descriptions of the emissions modeling methods categorized by pollutant and generally ordered to reflect the fidelity of the methods (i.e., more accurate methods are described first). The appendices provide coverage of supporting information including descriptions of aircraft performance methods and sources of data.

Although uncertainties associated with each method are conveyed as part of the methodology discussions (e.g., in Section 4), the last appendix provides a more dedicated discussion of uncertainties mainly relating to comparisons of the different methods to either "gold standard" data or methods.

4. PRINCIPAL CONSIDERATIONS IN COMPUTATION OF EMISSIONS

The following sections provide an overview of the three main categories of data that influence emissions. These include the engine, aircraft, and the atmosphere. Inherent within the engine and aircraft categories are both the characteristics of the equipment as well as their operations.

4.1 Engine Characteristics and Operations

Aircraft engine emissions are products of combustion of aviation fuel with air. Aviation fuel is composed of approximately 99.7% of hydrocarbons, represented as C_xH_y , and up to 0.3% sulfur (more typically in the 0.05% range). Products of combustion are primarily CO_2 and H_2O as well as trace levels of SO_x . Incomplete combustion leads to CO and THC. A portion of the THC emissions include trace amounts of toxic species referred to as Hazardous Air Pollutants (HAPs). Additional carbon is emitted in the form of soot and smoke. Due to the high temperatures of combustion and the presence of nitrogen, N_2 in the intake air, NO_x ($NO_x = NO + NO_2$) is also emitted. Many of the emissions described above are dependent on both the design and operation of the engine.

H_2O and CO_2 are products of complete combustion, and can mainly be reduced by developing more efficient engines that use less fuel. In the short term (25 years or less), reduction in CO_2 and H_2O will most likely be achieved by improving fuel efficiency since alternate fuels require major changes in aircraft and engine design, and the development of an infrastructure for delivery and storage. Pollutants such as THC, CO, and smoke are products of incomplete combustion and can be reduced by improvements in combustor design. NO_x are typically produced when nitrogen and oxygen in the air react in the combustor at flame temperatures above approximately 2800 °F. These conditions generally occur at high thrust levels such as take-off, climb-out and cruise. The amount of NO_x produced is also influenced by the amount of reaction time at high temperatures. Hence, to reduce NO_x , the engine must be designed to not only reduce the flame temperature but also the time (residence time) the air spends at high temperature. The challenge becomes greater as modern, more fuel efficient engines employ higher fan bypass ratios and operate at higher pressures which in turn result in higher flame temperatures making the NO_x reduction task ever more difficult. The engine manufacturer is constantly faced with trading NO_x with fuel burn (CO_2) and at times noise. Therefore, the optimized combustor design for emissions considers the trade of flame temperature and NO_x versus engine efficiency and the associated CO_2 and H_2O emissions. The content of sulfur in the jet fuel controls the level of SO_x emissions, not the combustor technology. Reducing the sulfur content would directly reduce SO_x emissions.

4.2 Aircraft Characteristics and Procedures

Aircraft can influence emissions based on the overall characteristics of the aircraft or airframe proper. Characteristics such as engine thrust ratings, weight of the aircraft, and lift and drag properties of the airframe are essential components in modeling aircraft performance to ultimately calculate fuel burn and emissions. Although there are different ways to model aircraft performance, a typical method involves the use of known (previously collected) aircraft data to predict thrust and fuel flow usually based on empirical equations developed from higher fidelity manufacturer model outputs and/or test data. Since emissions calculations are based on fuel burn, all of these aircraft data can have significant effects on emissions. In general, heavier aircraft and engines with higher thrust ratings will require more fuel and produce higher emissions.

In conjunction with aircraft characteristics, aircraft procedures also play an important role in modeling performance. Typically, performance models also require the use of procedural information such as an airline speed schedule, flap settings, etc. In addition to affecting the calculation of thrust for each mode, aircraft speeds also independently affect fuel burn calculations through the determination of flight duration and provides higher order effects for emissions calculations (depending on which method is used). Various operational procedures are often employed. The use of reduced thrust to reduce engine maintenance costs, continuous descent approach (CDA) to reduce noise and emissions impacts, and reduced vertical separation minimum (RVSM) to reduce airspace congestion are all examples of operational procedures that affect fuel burn and emissions through changes in thrust, speed, altitude, etc.

In assessing the changes to fuel burn and emissions caused by these aircraft characteristics and procedures, the tradeoffs between power settings and time need to be carefully considered. For example, mass emissions of some pollutants such as NO_x and CO₂ will increase with fuel flow. But for other pollutants such as CO and THC, an increase in fuel flow can result in either an increase or decrease depending on the actual fuel flow levels and the duration associated with this change.

4.3 Computational Reference Conditions

4.3.1 Atmospheric Conditions

Emissions vary according to the ambient conditions. The primary effects are caused by barometric pressure (which is also a function of altitude), temperature, and humidity. These atmospheric variables can have significant effects (e.g., greater than 20% on overall results). With increasing deviations from sea level conditions, the effects from these variables increases and are generally greatest for cruise.

Since most aircraft emissions analyses employ the internationally accepted ICAO emissions databank, reference conditions are established by these data. ICAO defines the reference atmospheric conditions to be identical to the International Standard Atmosphere (ISA) as the "atmospheric conditions to which all engine performance data should be corrected" for the purpose of certification. This atmosphere is defined in the Manual of the ICAO Standard Atmosphere with values at sea level indicated below (ICAO^a 1993):

- Pressure: 101 325 Pa
- Temperature: 15 °C

In addition, the reference atmospheric defines absolute humidity as 0.00634 kg water per kg dry air. During certification testing, ambient conditions are reported as follows:

- Barometric Pressure: kPa
- Temperature: °K
- Absolute Humidity: kg water/kg dry air

The final emission indices (EI) and fuel flows presented in the ICAO emissions databank represent values that have been corrected to the reference conditions.

4.3.2 Operating Conditions

As part of its certification definitions and emissions database, ICAO has promulgated three sets of reference operating conditions: Power settings, times-in-mode (TIM), and LTO profiles. ICAO defines four power settings as part of its LTO definition for subsonic engines with 26.7 kN or greater max installed thrust:

- Takeoff: 100%
- Climbout: 85%
- Approach: 30%
- Idle: 7%

The EI and fuel flow data collected during engine certification tests are processed to these power settings for inclusion within the ICAO emissions databank. Although the relevance of these settings have been questioned, especially in light of reduced thrust operations during takeoff and lower power usage under idle conditions, they still represent the international standard and the basic framework for regulatory considerations.

As part of the certification process development in the 1970s, ICAO established reference times for each of the four modes that occur under the LTO cycle as shown below:

- Takeoff: 0.7 min
- Climbout: 2.2 min
- Approach: 4 min
- Idle: 26 min

Since each airport is unique, and operational procedures vary, the actual times for these modes will vary. Comparisons against data from flight data recorders (FDR) have shown significant deviations from these TIM values; in some cases, greater than 100% difference (Fleuti 2004 and Patterson 2008). Therefore, these values may not provide accurate predictions of emissions at a given airport. However, they still provide a convenient supply of default data when resources are not available for obtaining more accurate information. As better understanding of average TIM values emerges and modelers implement more exacting processes, the reference values will likely need to be revised to follow suit.

The standard LTO profiles are based on the use of 3000 ft above airport field elevation (AFE) to define an artificial cap for the climbout and approach modes. The 3000 ft represents the extent of the LTO cycle and is based on an approximation of the mixing height at an airport. The actual convective mixing height typically varies dramatically during the day. Seasonal and meteorological influences also contribute to the strength of the diurnal characteristic mixing height. More accurate data or performance models can potentially be employed to determine better profiles.

5. COMPUTATIONAL PROCEDURES

The following sections concerning the modeling of NO_x, CO, and THC are tiered such that the highest fidelity method is presented first followed by methods with decreasing levels of accuracy. The most accurate method promulgated in this document is the P3T3 method followed by both BFFM2 and the DLR method representing the next tier down. In the bottom tier is the ICAO reference method. The basis for choosing one method over another depends on modelers' needs. Essentially, a balance between resources (including data accessibility) and accuracy must be determined.

5.1 Gaseous Emissions (NO_x, CO, and THC) – P3T3 Method

The P3T3 method for jet engines has been described in various texts including the IPCC 1999 document. The version provided here is essentially a facsimile of the one provided by Madden 2003 which is similar to the process defined in ICAO Annex 16, Volume II, to correct emissions certification data for variations in ambient conditions (ICAO^b 1993). To use this method, it is necessary to know the combustor inlet pressure (P3), temperature (T3), hence the name of the method, and the fuel-to-air ratio (FAR) at both the reference test condition and the operational condition being modeled.

5.1.1 Methodology

The methodology is presented in terms of EINO_x calculations, but also applies to EICO and ETHC with different parameters. The process for calculating EINO_x is illustrated in Figure 1.

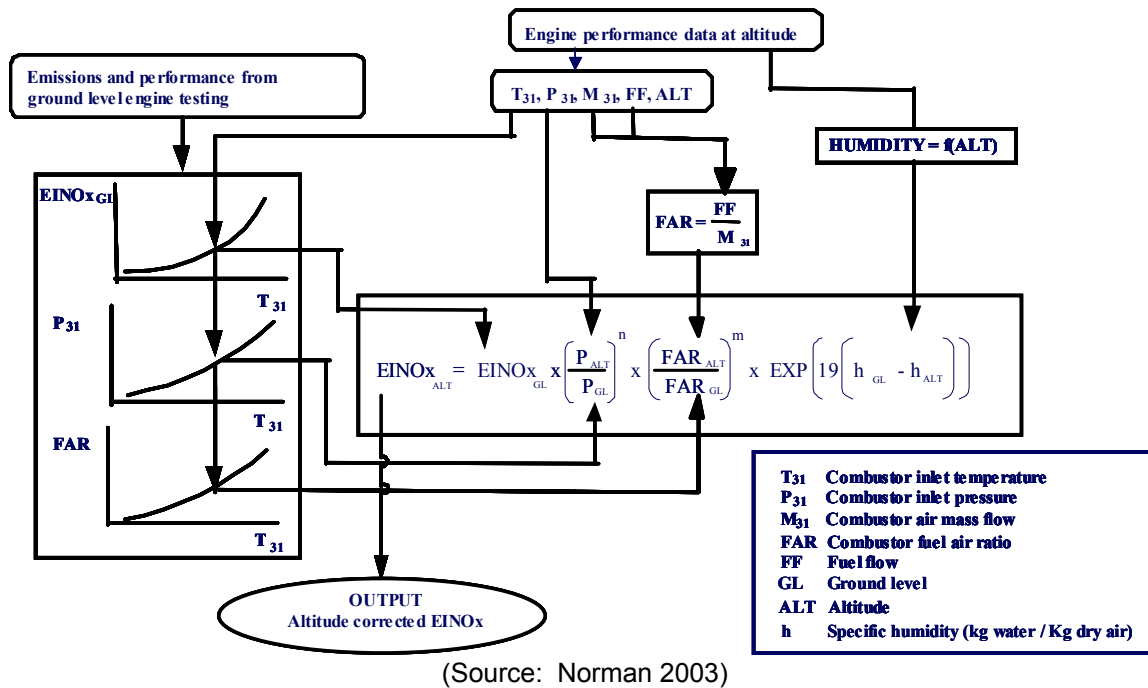


FIGURE 1 - P3T3 METHODOLOGY OF ALTITUDE NOx PREDICTION

First, EINOx, P3, and FAR from ground level measurements at reference conditions (e.g., ISA conditions at sea level) are plotted against combustor inlet temperature. The relationships provided by these plots are used to determine the reference EINOx, reference combustor inlet pressure, and reference FAR corresponding to the inlet temperature at the flight condition. The reference EINOx is then corrected for the difference in combustor inlet pressure and FAR between the ground level reference condition (REF) and the flight condition (FLT) using the following relationship:

$$EINOx_{FLT} = EINOx_{REF} \cdot \left(\frac{P3_{FLT}}{P3_{REF}} \right)^a \cdot \left(\frac{FAR_{FLT}}{FAR_{REF}} \right)^b \cdot e^{19(h_{REF} - h_{FLT})} \quad (\text{Eq. 1})$$

The values for the pressure and FAR exponents, a and b , are determined by conducting parametric tests either in a combustor test rig or an engine altitude facility. In addition to the P3 and FAR corrections, a humidity correction is also required as indicated by the exponential term. This is necessary as air cannot hold as much water due to the lower ambient temperatures with increasing altitudes. Certification data in the ICAO Databank are corrected to a humidity of .00634 g water per kg dry air (60% relative humidity, ISA day). Figure 2 shows how the humidity correction from ISA, sea level varies with altitude; the correction becoming larger at higher altitudes.

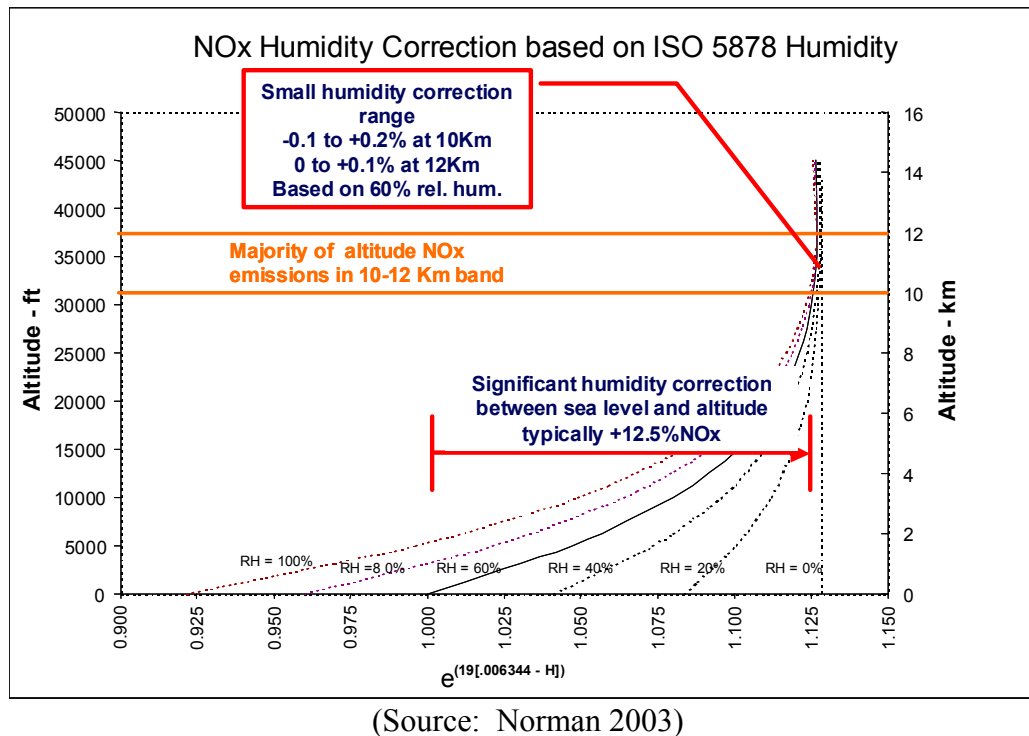


FIGURE 2 - HUMIDITY CORRECTION FOR ALTITUDE NOX

Thus, any ground level EINOx measurements, obtained at relatively high humidity, will increase by around 12 or 13% for an equivalent high altitude condition. ISO 5878 defines specific humidity (kg water to kg dry air) with varying altitude and relative humidity. It is clear from Figure 2 that at typical cruise altitudes, the error by choosing different relative humidity curves to describe the altitude condition is small because the air is so dry. 60% relative humidity should therefore be used if actual humidity is not available (as in the current ICAO Annex 16 procedure).

Engine manufacturers have gathered significant amounts of data, generated by rig and engine testing that have helped in defining the pressure coefficient to be used in the P3T3 method. Rig testing, where combustor inlet conditions are varied independently in order to determine their relative effect on NOx formation, have derived pressure exponents in the range 0.3 to 0.5 for typical cruise operation. A pressure exponent of 0.4 should be used for conventional combustion systems unless sufficient test data are available to support use of a different value. Past findings by CAEP technology working groups have shown that 0.4 is an appropriate value to use. Madden estimates that accuracy is within $\pm 11\%$ when using a pressure exponent of 0.4 (Madden 2003).

Data from engine manufacturers show that for a given T3, FAR is typically 10% richer at cruise than at ground level. However, for rich burn combustors (combustor primary zone richer than stoichiometric at take-off) the impact of this FAR change has been shown to be weak. Therefore, the recommended FAR exponent for a conventional combustion system is 0. This has also been shown to be an appropriate value to use from past findings by CAEP technology working groups.

The recommended pressure and FAR exponents do not necessarily apply to advanced "Lean Burn" combustion systems. Limited data in lean systems indicate the pressure exponent may be on the order of 0.2, and the FAR exponent may be on the order of 1.0. Therefore, specific values of pressure and FAR exponents for a lean burn combustion system should be determined in rig or altitude facility tests. In addition, any difference in staging strategy would need to be taken into account in such systems.

As previously indicated, the same basic method used for NOx may also be applied to CO and HC emissions, although actual pressure and FAR exponents for HC and CO are typically different from each other and may vary considerably depending on combustor design and engine operating conditions. ICAO Annex 16 recommends a pressure exponent of -1.0 and FAR exponent of 0 for both CO and HC. Correction for humidity is not recommended (ICAO^b 1993).

5.1.2 Example Calculations

Example calculations are presented here using the P3T3 method. It should be noted that the P3T3 method relies on data from a detailed thermodynamic engine model. Such a model is not openly available in most cases. Therefore, the calculations here are based on assumed values for the internal thermodynamic parameters. These calculations are presented strictly for clarifications of the methodology, and the results should not be compared against results from the other methods.

The calculations have been performed for a Trent 892 engine (with an ICAO UID of 2RR027) operating at a cruise condition. The input conditions for the calculation are:

- Altitude = 35 000 ft
- Mach = 0.82
- Standard day
- Engine fuel flow rate = 0.994 kg/s
- $P_a = 3.464 \text{ psia} = 23.880 \text{ kPa}$
- $T_a = 393.8 \text{ R} = -54.4 \text{ °C} = 218.8 \text{ K}$
- $RH = 60\% = 0.6$

The assumed thermodynamic conditions for the engine at this point are:

$P_3 = 12.46 \text{ bar}$
 $T_3 = 726.3 \text{ K}$
 $FAR = 0.0204$

The ICAO data (from Issue 15C) for the Trent 892 engine are shown in Table 2.

TABLE 2 - ICAO DATA FOR TRENT 892

Mode	EINOx (g/kg)	EICO (g/kg)	EIHC (g/kg)	Ref. Fuel Flow (kg/s)
Takeoff	45.7	0.28	0.01	3.91
Climbout	33.3	0.2	0	3.10
Approach	11.58	0.57	0	1.00
Idle	5.33	13.07	0.7	0.30

The assumed thermodynamic conditions for the engine at the four certification points are shown in Table 3.

TABLE 3 - ASSUMED THERMODYNAMIC CONDITIONS FOR TRENT 892

Thrust	P_3 (bar)	T_3 (K)	FAR
100%	41.23	896.0	0.02770
85%	36.71	870.0	0.02353
30%	17.14	725.8	0.01642
7%	6.84	568.9	0.01064

The calculation of the reference emission indices as functions of T3 has been performed using a linear interpolation on a log-log scale approach. This gives:

$$\log(EINOx_{REF}) = \log(11.58) + \frac{\log(726.3) - \log(725.8)}{\log(870.0) - \log(725.8)} \times (\log(33.30) - \log(11.58)) = 1.0655$$

$$EINOx_{REF} = 10^{1.0655} = 11.63 \text{ g / kg}$$

$$\log(EICO_{REF}) = \log(0.57) + \frac{\log(726.3) - \log(725.8)}{\log(870.0) - \log(725.8)} \times (\log(0.20) - \log(0.57)) = -0.2459$$

$$EICO_{REF} = 10^{-0.2459} = 0.57 \text{ g / kg}$$

$$\log(EIHC_{REF}) = \log(0.001) + \frac{\log(726.3) - \log(725.8)}{\log(870.0) - \log(725.8)} \times (\log(0.0001) - \log(0.001)) = -3.0038$$

$$EIHC_{REF} = 10^{-3.0038} = 0.00099 \text{ g / kg}$$

In the above, the zero values of EIHC at the 30% and 85% thrust certification points were set to minimum values of 0.001 and 0.0001, respectively, to avoid problems with the interpolation scheme. Similarly to the above calculations, the reference values for P3 and FAR are calculated as:

$$\log(P3_{REF}) = \log(17.14) + \frac{\log(726.3) - \log(725.8)}{\log(870.0) - \log(725.8)} \times (\log(36.71) - \log(17.14)) = 1.2353$$

$$P3_{REF} = 10^{1.2353} = 17.19 \text{ bar}$$

$$\log(FAR_{REF}) = \log(0.01642) + \frac{\log(726.3) - \log(725.8)}{\log(870.0) - \log(725.8)} \times (\log(0.02353) - \log(0.01642))$$

$$= -1.7840$$

$$FAR_{REF} = 10^{-1.7840} = 0.01644$$

The corrections for atmospheric effects at altitude include one for humidity effects. The saturation vapor pressure and humidity ratio are calculated using equations (8 and 9) that are later defined in this document:

$$P_{sat} = 6.107 * 10^{\frac{7.5 * (-54.4)}{237.3 - 54.4}} = 0.03590 \text{ mbar}$$

$$\omega = \frac{(0.62197058 * 0.6 * 0.03590)}{(3.464 * 68.9473) - (0.6 * 0.03590)} = 0.000056 \text{ kg/kg of dry air.}$$

Hence, using Equation 1 for EINOx and similar implementations for EICO and EIHC,

$$EINOx = 11.63 \times \left(\frac{12.46}{17.19} \right)^{0.4} \left(\frac{0.0204}{0.0164} \right)^{0.0} e^{(19(0.00634 - 0.000056))} = 11.52 \text{ g/kg}$$

$$EICO = 0.57 \times \left(\frac{12.46}{17.19} \right)^{-1.0} \left(\frac{0.0204}{0.0164} \right)^{0.0} = 0.79 \text{ g/kg}$$

$$EIHC = 0.00099 \times \left(\frac{12.46}{17.19} \right)^{-1.0} \left(\frac{0.0204}{0.0164} \right)^{0.0} = 0.0014 \text{ g/kg}$$

5.1.3 Assumptions and Limitations

The main limitation of the P3T3 method is that it is data intensive. As discussed, it is necessary to know P3, T3, and FAR at the reference test condition unless the associated exponent is zero. Reference emissions indices are available from the ICAO databank, but reference P3, T3, and FAR are not provided. Although detailed reference engine data are measured during emissions certification tests, the data are typically proprietary and are therefore, difficult to obtain.

The P3T3 method is currently limited to jet engines. Turboprops are not covered by the method.

Overall engine pressure ratio at the rated thrust condition is provided in the ICAO databank, so it might be possible to develop a reasonable estimate of combustor inlet temperature based on estimated compression efficiency, but a sophisticated engine modeling capability would be needed to estimate P3 and T3 over the engine thrust range.

Estimating P3 and T3 at a given flight condition can also be problematic. P3 and T3 could either be measured or calculated. High quality measurements of engine P3 and T3 are difficult and expensive to obtain. On some engines with full authority electronic controls, P3 and T3 are measured and recorded on a continuous basis. However, these data are not typically downloaded unless there is a specific reason to do so (e.g., due to an engine or control malfunction). P3 and T3 can be calculated using a detailed engine performance analytical model of the engine (i.e., cycle deck) if flight altitude, Mach number, thrust level (or fuel flow), ambient pressure, and ambient temperature are known. However, engine performance models are not typically available to the general public.

The accuracy of NOx estimates using recommended pressure exponents has been estimated at $\pm 11\%$ where P3 and T3 at reference conditions are known. The accuracy of CO and HC estimates have not been established (Madden 2003).

5.2 Gaseous Emissions (NOx, CO, and THC) – BFFM2

Developed by the Boeing Company, the Boeing Fuel Flow Method 2 (BFFM2) was first presented to the ICAO CAEP WG3 Certification Subgroup on March 6, 1995 with a subsequent inclusion of the methodology in an appendix of an emissions inventory report developed by Boeing. BFFM2 was developed to expand upon Boeing's "method 1" by allowing non-standard day condition computations and without the need to know combustor inlet temperature (T_3) and pressure (P_3). An updated paper on this methodology has been published as a technical paper by SAE (Dubois 2006).

BFFM2 involves the use of the ICAO or other suitable certification-type emissions databank (see Appendix E) to model emissions indices of CO, THC, and NOx. For simplicity, this ICAO databank will be used for discussions related to BFFM2, but it should be understood that similar databases will also apply. The key components of the method are semi-empirical methods to adjust for atmospheric effects and the development of a relationship between EI and fuel flow. This allows a predicted fuel flow (i.e., for a flight segment) computed from a model or from measurements to be used to predict emissions. Figure 3 shows an overview of the methodology based on calculation of emissions for a flight segment.

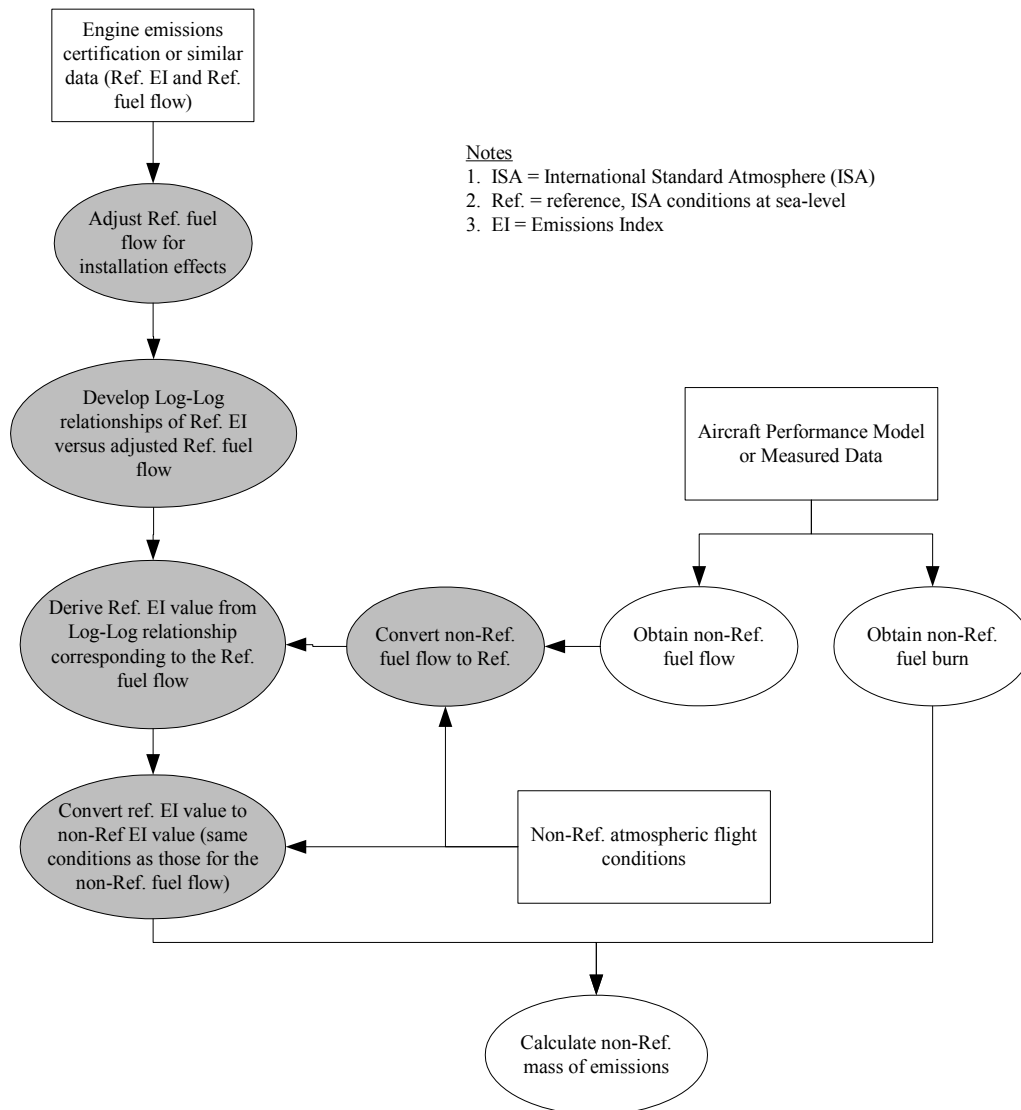


FIGURE 3 - NO_x, CO, AND THC EMISSIONS COMPUTATIONS USING BFFM2

BFFM2 does not actually compute emissions; rather, it predicts the emission index (EI) values that can be used with fuel burn to compute mass of emissions. The grayed ellipses in Figure 3 indicate the boundaries of BFFM2. The method can be used to calculate EIs for varying levels of resolution including segments and modes of a flight. For clarity, data and results corresponding to flight conditions are referred to as “non-reference” values while the fuel flow and emissions in the ICAO database are referred to as “reference” values because they correspond to the reference condition: International Standard Atmosphere (ISA) at sea-level.

5.2.1 Methodology

The first step involves the adjustment of reference fuel flow values from the ICAO databank for installation effects which refer to the difference between data obtained from an engine that was tested on a test stand (e.g., ICAO certification data) and an engine that is installed on an aircraft. The effects are due to engine air bleed which occur when the engines are installed on an aircraft. These effects are likely aircraft and engine specific. However, in the absence of available data, BFFM2 suggests “general correction” (adjustment) factors as shown in Table 4.

TABLE 4 - ADJUSTMENT FACTORS FOR INSTALLATION EFFECTS

Mode	Power Setting (%)	Adjustment Factor
Takeoff	100	1.010
Climbout	85	1.013
Approach	30	1.020
Idle	7	1.100

These adjustment factors are multiplied by fuel flow from the ICAO databank for each mode. The next step is to develop a Log-Log relationship between EI and fuel flow, both at reference conditions. Figure 4 shows example plots of the four certification data points on Log-Log scales for each of the three pollutants.

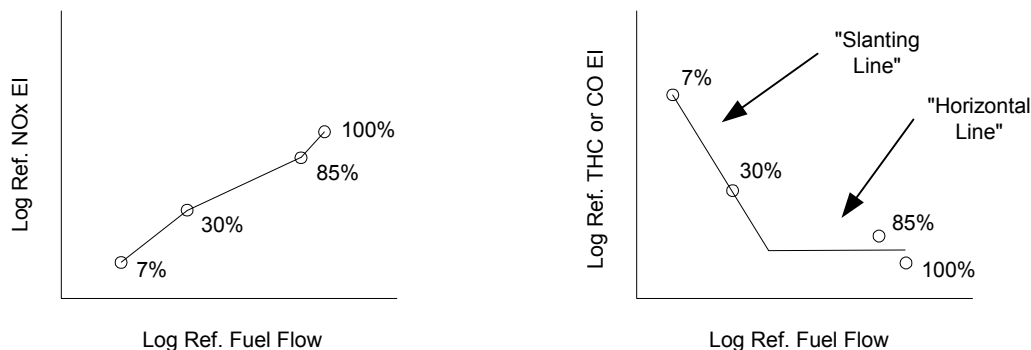


FIGURE 4 - EXAMPLE LOG-LOG PLOTS OF NOX, CO, AND THC AS PRESCRIBED BY BFFM2

As shown in the plots, NOx EIs are modeled using a point-to-point fit (e.g., “connect the dots” approach) on Log-Log scales. Therefore, points in-between each pair of adjacent certification points are determined through linear interpolations on the Log-Log scales. In general, this point-to-point approach will more accurately reflect engine behavior since it will tend to capture the inflection points that a single regressed line may miss. For CO and THC EIs, two lines are used to form a bilinear fit. The first line is a point-to-point fit between the two lower power setting points (i.e., 7% and 30%). Hereinafter, this line will be referred to as the “slanting line” for clarity. The second line is denoted in the right hand panel of Figure 4 as “horizontal” and is the linear average of the non-log values at the two higher power setting points (i.e., 85% and 100%). The two lines are then extrapolated until they intersect.

These plots represent the “standard” behavior for most of the data from the ICAO and similar databases. But the data for some engines do not exhibit this behavior for THC and CO. Because of this, additional methods have been developed to account for these other cases. Figure 5 shows the two cases where the certification data from ICAO behaves differently from the standard cases.

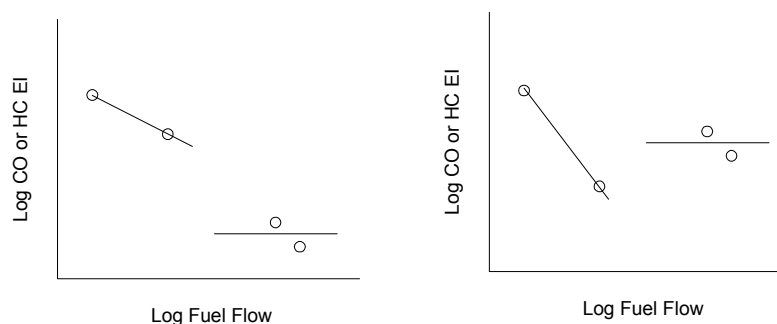


FIGURE 5 - NON-STANDARD DATA BEHAVIOR

Additional methods to account for these non-standard behavior basically provide solutions to “tie” the disconnected lines shown in Figure 5. These solutions are illustrated in Figure 6 as thick “middle lines.”

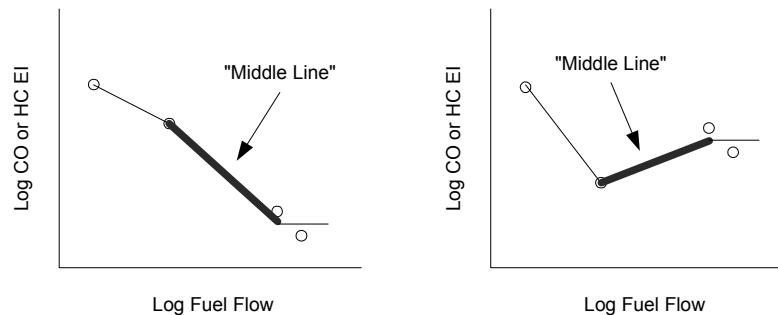


FIGURE 6 - ADDITIONAL METHODS TO ACCOUNT FOR NON-STANDARD BEHAVIOR OF THE ICAO DATA

As shown in Figure 6, the left end of each “middle line” starts at the 30% power setting point and the right end is located at the intersection formed by an imaginary vertical line through the 85% power setting point and the horizontal line between the two higher power setting points.

In addition to these main modeling steps, supplementary methods have also been developed to address some exceptional issues. The first of these involves the possibility of extrapolating the plots of EI versus fuel flow below the 7% power setting. Although this is the standard ICAO power setting used to represent idling and taxiing power, actual power usage can be less. While the changes to NO_x may not be significant when modeling below 7%, the changes to THC and CO can be significant. As a result, extrapolations below are recommended to properly model emissions, but care must be taken since erroneously high emissions could be generated for some engines.

The second supplementary issue concerns the modeling of zero values from the certification data, especially concerning EITHC values. Since zero values cannot be converted to Logs, a substitution to a small value is recommended. For the 85% and 100% power points or if all power point EIs are zero, any value $\leq 10^{-4}$ should suffice. If the 7% power point is non-zero and the 30% power point is zero, then values $< 10^{-3}$ may result in excessive extrapolation below the 7% power setting. These solutions are reasonable since the zero values in the ICAO data likely represents small values that were rounded to zero as opposed to actually implying zero emissions.

The third issue also concerns the situation when the ICAO data for an engine is missing. That is, the entries for EI or fuel flow may simply be filled with a non-numerical indicator such as “-.” In these cases, the missing data could potentially be derived from the remaining data and any other sources if the various information allows this. The missing data could also either be substituted or obtained by averaging with another engine’s data (identical or similar) listed in the ICAO databank.

After the log-log relationships have been established, the modeled or measured fuel flow at flight conditions is converted to reference conditions. The resulting reference fuel flow is used with the log-log relationships to derive the corresponding EINO_x, EICO, and EITHC at reference conditions. Then these are converted to non-reference, flight conditions. Equations 2 through 10 provide the conversion equations used to account for all of these atmospheric effects.

$$FF_{ref} = \frac{FF}{\delta} \theta^{3.8} e^{0.2M^2} \quad (\text{Eq. 2})$$

$$EINO_x = EINO_{x,ref} e^H \left(\frac{\delta^{1.02}}{\theta^{3.3}} \right)^y \quad (\text{Eq. 3})$$

$$EITHC = EITHC_{ref} \left(\frac{\theta^{3.3}}{\delta^{1.02}} \right)^x \quad (\text{Eq. 4})$$

$$EICO = EICO_{ref} \left(\frac{\theta^{3.3}}{\delta^{1.02}} \right)^x \quad (\text{Eq. 5})$$

$$\theta = \frac{T_a}{288.15} \quad (\text{Eq. 6})$$

$$\delta = \frac{P_a}{101325} \quad (\text{Eq. 7})$$

$$H = -19.0(\omega - 0.00634) \quad (\text{Eq. 8})$$

$$\omega = \frac{(0.62197058 * RH * P_{sat})}{(P_{psia} * 68.9473) - (RH * P_{sat})} \quad (\text{Eq. 9})$$

$$P_{sat} = 6.107 * 10^{\frac{7.5 * T_{ac}}{237.3 + T_{ac}}} \quad (\text{Eq. 10})$$

where

FF_{ref} = Fuel flow at reference conditions (kg/s)
 FF = Fuel flow at non-reference conditions (kg/s)
 $EINO_x$ = NO_x EI at non-reference conditions (g/kg)
 $EINO_{x,ref}$ = NO_x EI at reference conditions (g/kg)
 $EICO$ = CO EI at non-reference conditions (g/kg)
 $EICO_{ref}$ = CO EI at reference conditions (g/kg)
 $EITHC$ = THC EI at non-reference conditions (g/kg)
 $EITHC_{ref}$ = THC EI at reference conditions (g/kg)
 M = Mach number
 θ = Temperature ratio (ambient to sea level)
 δ = Pressure ratio (ambient to sea level)
 T_a = Ambient temperature (K)
 T_{ac} = Ambient temperature (°C)
 P_a = Ambient pressure (Pa)
 P_{psia} = Ambient pressure (psia)
 ω = Humidity ratio (kg H₂O/kg of dry air)
 H = Humidity coefficient
 RH = Relative humidity
 P_{sat} = Saturation vapor pressure (mbar)
 x = P3T3 exponent (default value is 1.0)
 y = P3T3 exponent (default value is 0.5)

Equations 2 through 5 are used to convert fuel flow and EI values from non-reference (at-altitude) conditions to reference conditions and vice versa. The reference fuel flow and EI input values are obtained from the ICAO database while the fuel flow and Mach number associated with a flight segment is obtained from an aircraft performance model or from measurement. All of the independent atmospheric parameters (T_a , P_a , etc.) corresponding to the flight segment must also be provided as inputs.

5.2.2 Example Calculations

The example calculations presented here were derived from the SAE BFFM2 technical paper (DuBois 2006). These calculations are presented strictly for clarifications of the methodology, and the results should not be compared against results from other methods. Input conditions for this example are:

- Altitude = 39,000 ft
- Mach = 0.84
- Standard day
- Engine fuel flow rate = 7000 lb/hr/engine = 0.882 kg/s
- P_a = 2.854 psia

- $\delta = 0.1942$
- $T_a = 390 \text{ R} = -56.5^\circ\text{C}$
- $\theta = 0.7519$
- $\text{RH} = 60\% = 0.6$
- P3T3 y exponent = 0.5
- P3T3 x exponent = 1.0

These values correspond to a cruise point or segment of a flight trajectory using the Trent 892 engine with an ICAO UID of 2RR027. The pertinent ICAO data (from Issue 15C) for this engine are shown in Table 5.

TABLE 5 - ICAO DATA FOR TRENT 892 ENGINE

Mode	Ref. EINOx (g/kg)	Ref. EICO (g/kg)	Ref. EITHC (g/kg)	Ref. Fuel Flow (kg/s)
Takeoff	45.7	0.28	0.01	3.91
Climbout	33.3	0.2	0	3.10
Approach	11.58	0.57	0	1.00
Idle	5.33	13.07	0.7	0.30

The ICAO Ref. fuel flows are adjusted for installation effects as indicated in Table 6.

TABLE 6 - FUEL FLOW ADJUSTMENT CALCULATIONS

Mode	Ref. Fuel Flow (kg/s)	Adjustment Factor	Adjusted Ref. Fuel Flow (kg/s)
Takeoff	3.91	X 1.010 =	3.95
Climbout	3.10	X 1.013 =	3.14
Approach	1.00	X 1.020 =	1.02
Idle	0.30	X 1.100 =	0.33

The adjusted ref. fuel flows and ref. EIs are converted to Log values and plotted as indicated in Figure 7 through Figure 9.

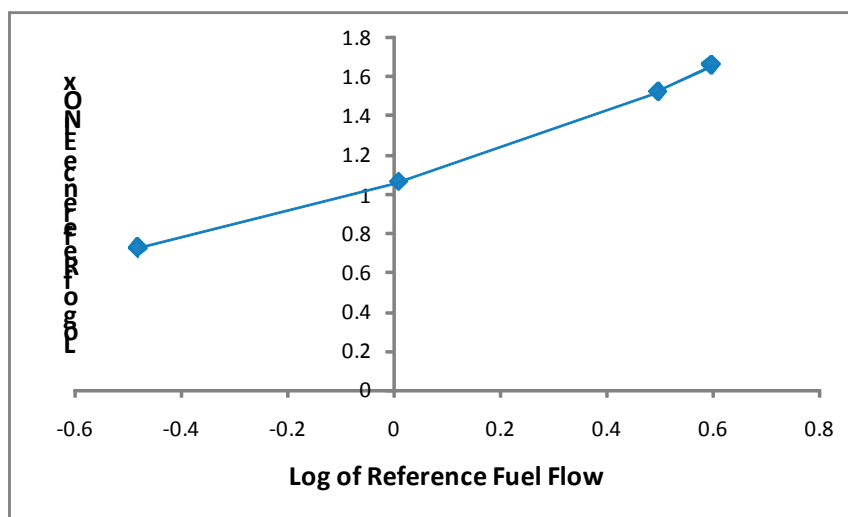


FIGURE 7 - LOG OF REFERENCE EINOX VERSUS LOG OF REFERENCE FUEL FLOW

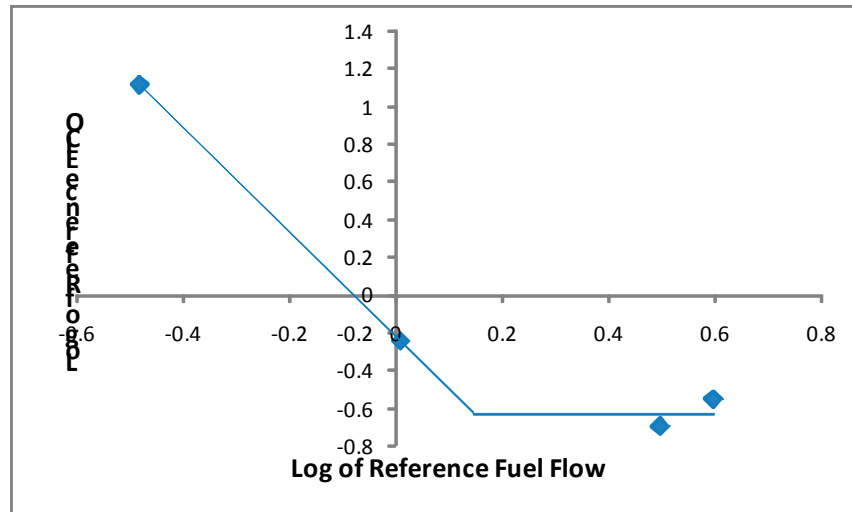


FIGURE 8 - LOG REFERENCE EICO VERSUS LOG OF REFERENCE FUEL FLOW

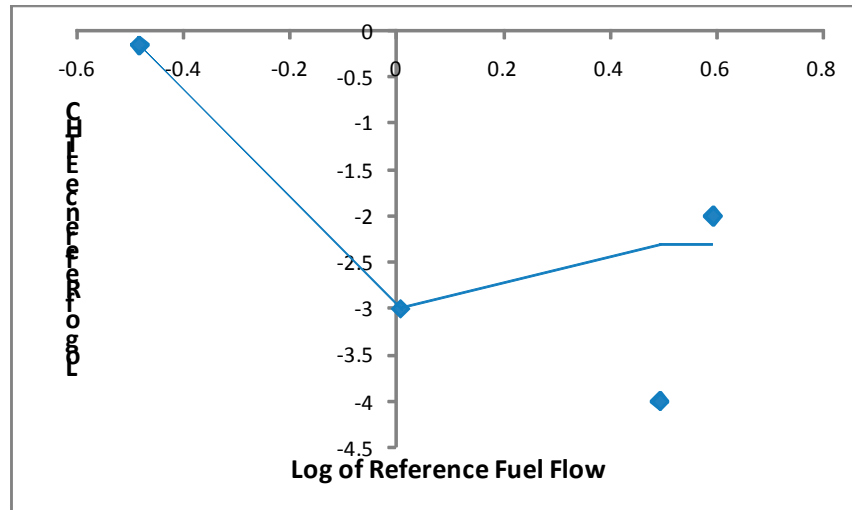


FIGURE 9 - LOG OF REFERENCE EITHC VERSUS LOG OF REFERENCE FUEL FLOW

The relationships between these EIs and fuel flows can also be expressed as equations for use in computer programs through the use of Log functions. Since the THC_{ref} values are zeros for the 85% and 30% power settings (and non-zero for the 7% power setting), they were substituted with 10^{-4} and 10^{-3} , respectively.

Using Equation 2, the reference fuel flow is computed as follows:

$$FF_{\text{ref}} = 0.882 \frac{.7519^{3.8}}{0.1942} e^{0.2 \cdot 0.84^2} = 1.77 \text{ kg/s}$$

Using the previously defined EI versus fuel flow relationships, the NOx_{ref} , EICO_{ref} , and $\text{EITHC}_{\text{ref}}$ values corresponding to this FF_{ref} are: 19.43 g/kg, 0.24 g/kg, and 0.0022 g/kg, respectively. The saturation vapor pressure, humidity ratio, and the humidity coefficient are calculated using equations 8-10:

$$P_{\text{sat}} = 6.107 * 10^{\frac{7.5 * (-56.5)}{237.3 - 56.5}} = 0.02773 \text{ mbar}$$

$$\omega = \frac{(0.62197058 * 0.6 * 0.02773)}{(2.854 * 68.9473) - (0.6 * 0.02773)} = 0.000053 \text{ kg/kg of dry air}$$

$$H = -19.0(0.000053 - 0.00634) = 0.119453$$

The resulting EI values for the point or segment at non-reference conditions are:

$$EINO_x = 19.43e^{0.119453} \frac{0.1942^{1.02}}{0.7519^{3.3}} = 15.19 \text{ g/kg}$$

$$EICO = 0.24 \frac{0.7519^{3.3}}{0.1942^{1.02}} = 0.50 \text{ g/kg}$$

$$EITHC = 0.0022 \frac{0.7519^{3.3}}{0.1942^{1.02}} = 0.00457 \text{ g/kg}$$

5.2.3 Assumptions and Limitations

One of the assumptions associated with the use of BFFM2 is that the Log-Log curve-fits will produce acceptable fidelity for the intended use. An assessment by the ICAO Committee on Aviation Environmental Protection's (CAEP) Working Group 3 (WG3) has shown that when comparing to finer certification data, the Log-Log curve fits generally show accuracy to within +/-10% for individual points for each of the three pollutants. However, at lower power settings, the errors for CO and THC can be greater. Between 7% and 30%, the errors were estimated to be around 10% for CO but up to 15% for HC. Below 7%, the errors could be significantly greater and considerable care must be taken in modeling in this regime.

These ICAO findings correspond well with the various validation-type assessments that have been conducted using altitude measured data from several measurement campaigns which were summarized in IPCC 1999 as assessments of "fuel flow methods." The summary indicates a difference between measured and modeled cruise NO_x EIs of 12% (underestimate) on average. In addition, altitude chamber testing and relative comparisons to P3T3 methods for a variety of aircraft and flight missions showed NO_x EI errors of 5-10% and 13% maximum (with 6% standard deviation), respectively. The Boeing SAE BFFM2 paper also presents some relative comparisons against P3T3 results (DuBois 2006). These comparisons show BFFM2 predictions of EI NO_x for several engines at various operating conditions to be within 10% to 15% of the P3T3 results. Up to 60% of the differences have been attributed to the humidity correction used in BFFM2 (DGCAN 2000). For CO and THC, the errors are expected to be much greater. The uncertainty may be further exacerbated in situations where the middle lines as indicated in Figure 4 need to be used in order to approximate engine behavior between the 30% and 85% power settings. These accuracy levels need to be considered when applying this method.

Another assumption deals with the fuel flows applied to this method. Since each set of ICAO data are specific to an engine, the fuel flow applied to the Log-Log relationship should ideally be specific to the engine as well. Some performance models promote the airframe rather than the engine in modeling the fuel flow of the aircraft. As a result, a disconnect can exist between the modeled fuel flow and the ICAO reference fuel flows used to form the Log-Log relationships. Therefore, the ramifications of such a disconnect need to be considered when using BFFM2. However, since the overall weight and size of an aircraft will tend to dictate the power and fuel flow required to create lift and movement, different engines that are commonly used on the same airframe will also tend to have similar power ratings and fuel flows, especially at cruise. The overall effect is that as long as the engines assigned to an airframe are logical (e.g., assigned based on a distribution from a fleet database), the effects of any disconnects will tend to be small.

A limitation with BFFM2 is that it is inappropriate for use with staged combustors (e.g., dual annular combustors or DAC). Since the EI versus fuel flow plots of THC and CO do not exhibit the aforementioned characteristics, neither the standard or modified bilinear plots can be developed. Therefore, BFFM2 currently cannot be used with DAC engines. However, if detailed information is available on the staging characteristics and these are reflected in the curve fits (e.g., using more than one curve fit), then the method could potentially be applied to each separate regime of staging.

Although the methodology described in this section is intended to be used with the ICAO certification database of jet engine data, BFFM2 has been used with similar datasets for turboprops (FAA 2005 and 2007). Further tests will need to be conducted to better understand the method's applicability to turboprops.

5.3 Gaseous Emissions (NO_x, CO, and THC) – DLR Method

Developed by DLR and described under Lecht 2001 and Döpelheuer 1998, the DLR Method allows the calculation of emissions indices for NO_x, CO and THC for any in-flight condition of an engine. For calculating EINO_x, the DLR Method employs a fuel flow methodology requiring the use of the ICAO or other suitable certification-type emissions databank (see Appendix E). For simplicity, the ICAO databank will be used to describe this method. Figure 10 shows an overview of the methodology based on calculation of NO_x emissions for a flight segment.

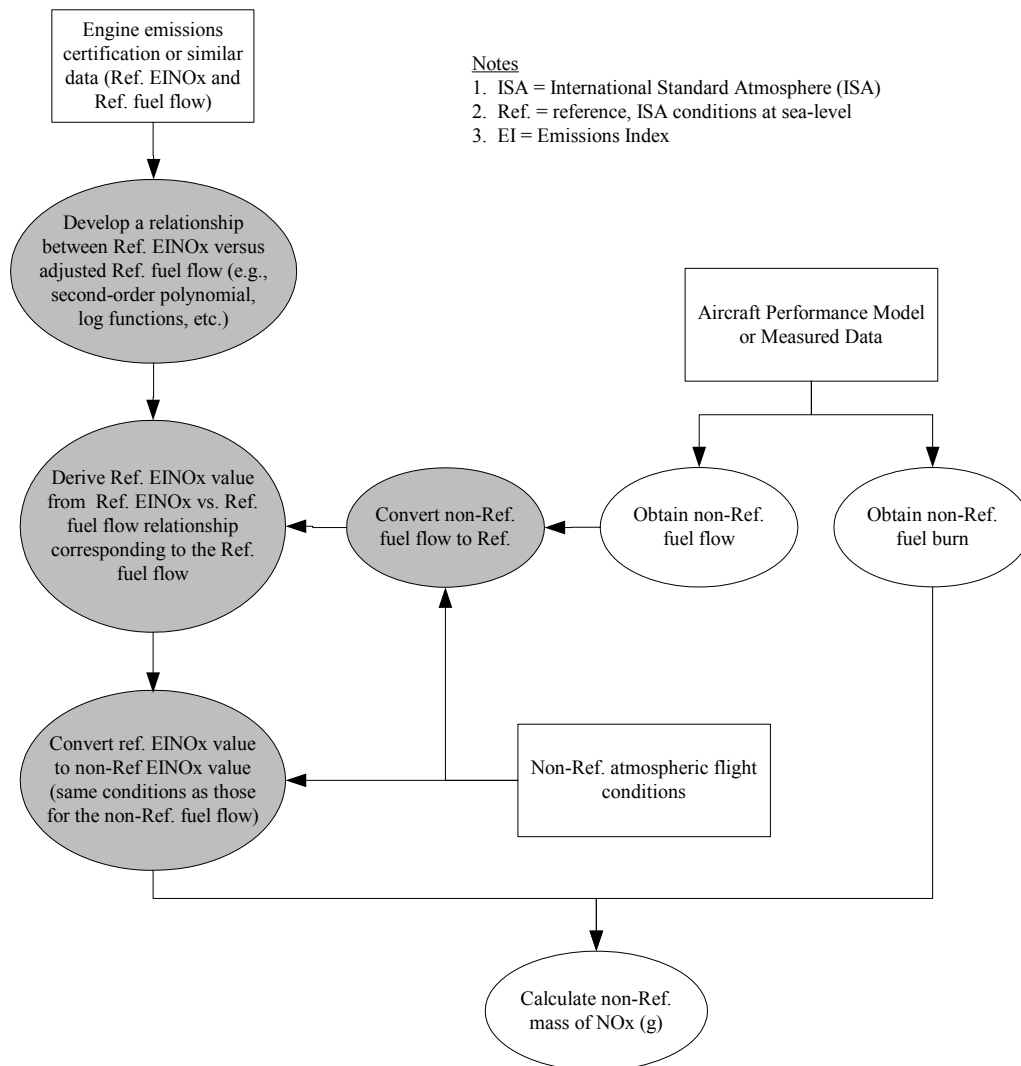


FIGURE 10 - NO_x EMISSIONS COMPUTATIONS USING THE DLR METHOD

For EICO and EITHC computations, the combustor inlet conditions must be known similar to the P3T3 method. As summarized in Figure 11, computations of EICO and EITHC for a flight segment require the ICAO data as well as the combustor inlet conditions at both the reference and non-reference (in-flight) conditions.

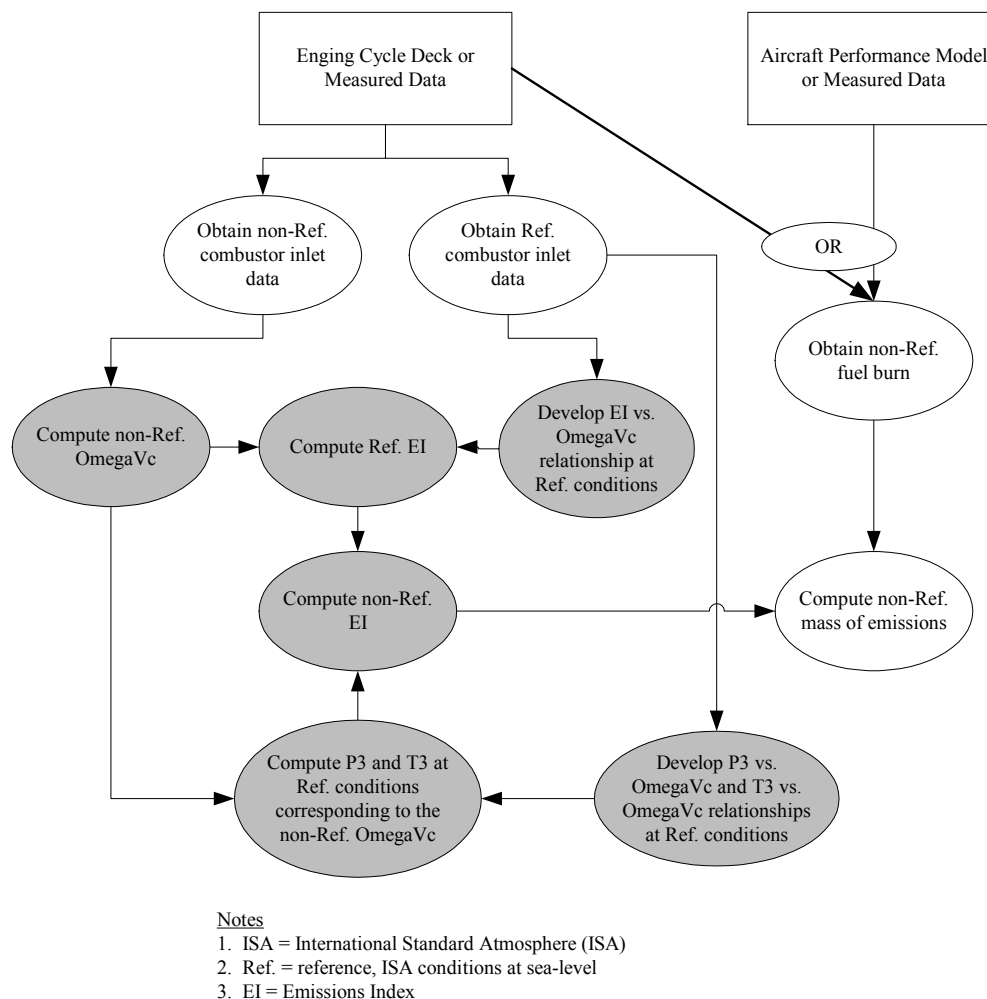


FIGURE 11 - CO AND THC EMISSIONS COMPUTATIONS USING THE DLR METHOD

The methods do not actually compute emissions; rather, they predict the EI values that can be used with fuel burn to compute mass of emissions. The grayed ellipses in Figure 10 and Figure 11 indicate the boundaries of the DLR Method. The method can be used to calculate EIs for varying levels of resolution including segments and modes of a flight. For clarity, the predicted fuel flow and emissions corresponding to at-altitude conditions are referred to as “non-reference” values while the fuel flow and emissions in the ICAO database are referred to as “reference” values because they correspond to the reference condition: International Standard Atmosphere (ISA) at sea-level.

5.3.1 Calculation of NO_x Emissions Indices

To calculate EINO_x, the key components of the fuel flow methodology within the DLR Method are conversions to account for atmospheric effects and the development of a relationship between fuel flow and emissions indices. The first step involves obtaining modelled or measured fuel flow and then correcting to reference conditions. Corrections for atmospheric effects are accounted for based on a gas turbine similarity scheme that takes advantage of the fact that fuel flow and NO_x emissions both follow engine load performance in a similar manner. The following equations are used to make these atmospheric corrections:

$$FF_{ref} = \frac{FF}{\delta_t \sqrt{\theta_t}} \quad (\text{Eq. 11})$$

$$EINO_x = EINO_{x_{ref}} \cdot \delta_t^a \cdot \theta_t^d \cdot e^{19.000634 - \omega} \quad (\text{Eq. 12})$$

$$\theta_t = \frac{T_{tot,1}}{288.15} \quad (\text{Eq. 13})$$

$$\delta_t = \frac{P_{tot,1}}{101325} \quad (\text{Eq. 14})$$

$$T_{tot,1} = T_a (1 + 0.2M^2) \quad (\text{Eq. 15})$$

$$P_{tot,1} = P_a (1 + 0.2M^2)^{3.5} \quad (\text{Eq. 16})$$

where

FF_{ref} = Fuel flow at reference conditions (kg/s)

FF = Fuel flow at non-reference conditions (kg/s)

$EINOx$ = NOx EI at non-reference conditions (g/kg)

$EINOx_{ref}$ = NOx EI at reference conditions (g/kg)

θ_t = Temperature ratio (ambient to sea level)

δ_t = Pressure ratio (ambient to sea level)

a = Pressure exponent (default $a = 0.4$)

d = Temperature exponent (default $d = 3.0$)

$T_{tot,1}$ = Total (stagnation) temperature corrected for flight speed (K)

$P_{tot,1}$ = Total (stagnation) pressure corrected for flight speed (Pa)

T_a = Ambient temperature (K)

P_a = Ambient pressure (Pa)

M = Mach number

ω = humidity ratio based on a suitable methodology (g H_2O / g of dry air)

The pressure and temperature exponents (a and d) can be obtained from thermodynamic engine simulation. The relationship between the fuel flow and $EINOx$ values from the ICAO databank is developed using a curve-fitting method, typically based on a second-order polynomial fit as indicated in Figure 12.

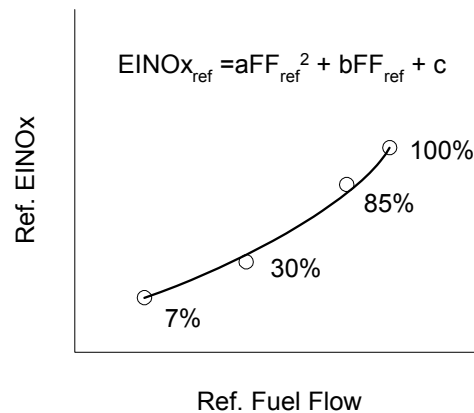


FIGURE 12 - EXAMPLE NOx EI VERSUS FUEL FLOW CURVE FIT AS PRESCRIBED BY THE DLR METHOD

Although a second-order polynomial interpolation procedure is generally sufficient, other curve fitting methods which reasonably represent the engine operation, such as Log and exponential functions. The resulting relationship is then used to obtain the reference $EINOx$ value in-between the certification power points corresponding to the starting fuel flow. This reference $EINOx$ is adjusted to reflect the non-reference (flight) conditions using Equation 12.

In addition to these main modeling steps, supplementary methods have also been developed to address a couple of exceptional issues. The first of these involves the possibility of extrapolating the plots of EI versus fuel flow below the 7% power setting. Although this is the standard ICAO power setting used to represent idling and taxiing power, actual power usage can be less. Therefore, extrapolations below 7% are recommended to properly model emissions, but care must be taken to prevent erroneous modeling on a case-by-case basis.

Another issue concerns the situation when the ICAO data for an engine is missing. That is, the entries for EI or fuel flow may simply be filled with a non-numerical indicator such as “-.” In these cases, the missing data could potentially be derived from the remaining data and any other sources if the various information allows this. The missing data could also either be substituted or obtained by averaging with another engine’s data (identical or similar) listed in the ICAO databank.

5.3.2 Calculation of CO and THC Emissions Indices

As indicated in Figure 11, the calculation of in-flight HC and CO emissions indices are performed using engine combustor inlet data which is used to represent combustor loading. Potentially this can describe the physical processes more accurately than fuel flow, but it requires the burden of obtaining the combustor inlet data. The method involves calculation of a ΩV_c term which is the reciprocal of a combustor loading parameter multiplied by the combustor volume (V_c):

$$\Omega V_c = \frac{W_{air}}{p3^{1.8} e^{\frac{T3}{300}}} \quad (\text{Eq. 17})$$

where

ΩV_c = Inverse of combustor loading parameter multiplied by combustor volume ($\text{kg}/\text{bar}^{1.8}\text{s}$)

W_{air} = Mass flow of air (kg/s)

$P3$ = Combustor inlet pressure at non-reference conditions (bar)

$T3$ = Combustor inlet temperature at non-reference conditions (K)

This equation is based on correlating engine efficiency with combustor loading. The combustor volume (V_c) has been included as part of this term for simplicity since it is a constant. Once the ΩV_c term is calculated, it is used to compute the corresponding reference EI value from a polynomial fit such as that represented by Equation 18 and exemplified in Figure 13.

$$EI_{ref} = a(\Omega V_c)_{ref}^2 + b(\Omega V_c)_{ref} + c \quad (\text{Eq. 18})$$

where

EI_{ref} = EICO or EITHC EI at reference conditions (g/kg)

a, b, c = Regression coefficients