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Methodology to Estimate Particulate Matter Emissions from Certified Commercial Aircraft Engines

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ABSTRACT

Today, about one-fourth of U.S. commercial service airports, including 41 of the busiest 50, are either in nonattainment or maintenance areas per the National Ambient Air Quality Standards. U.S. aviation activity is forecasted to triple by 2025, while at the same time, the U.S. Environmental Protection Agency (EPA) is evaluating stricter particulate matter (PM) standards on the basis of documented human health and welfare impacts. Stricter federal standards are expected to impede capacity and limit aviation growth if regulatory mandated emission reductions occur as for other non-aviation sources (i.e., automobiles, power plants, etc.). In addition, strong interest exists as to the role aviation emissions play in air quality and climate change issues. These reasons underpin the need to quantify and understand PM emissions from certified commercial aircraft engines, which has led to the need for a methodology to predict these emissions. Standardized sampling techniques to measure volatile and nonvolatile PM emissions from aircraft engines do not exist. As such, a first-order approximation (FOA) was derived to fill this need based on available information. FOA1.0 only allowed prediction of nonvolatile PM. FOA2.0 was a change to include volatile PM emissions on the basis of the ratio of nonvolatile to volatile emissions. Recent collaborative efforts by industry (manufacturers and airlines), research establishments, and regulators have begun to provide further insight into the estimation of the PM emissions. The resultant PM measurement datasets are being analyzed to refine sampling techniques and progress towards standardized PM measurements. These preliminary measurement datasets also support the continued refinement of the FOA methodology. FOA3.0 disaggregated the prediction techniques to allow for independent prediction of nonvolatile and volatile emissions on a more theoretical basis. The Committee for Aviation

Environmental Protection of the International Civil Aviation Organization endorsed the use of FOA3.0 in February 2007. Further commitment was made to improve the FOA as new data become available, until such time the methodology is rendered obsolete by a fully validated database of PM emission indices for today's certified commercial fleet. This paper discusses related assumptions and derived equations for the FOA3.0 methodology used worldwide to estimate PM emissions from certified commercial aircraft engines within the vicinity of airports.

INTRODUCTION

Aviation activity within the United States is forecasted to potentially triple by 2025.¹ At the same time, the U.S. Environmental Protection Agency (EPA) is evaluating impacts to human health and welfare to potentially set stricter particulate matter (PM) standards. Stricter pollution limitation embodied in law and regulations is expected to impede capacity and limit aviation growth, especially as aviation emissions increase against regulatory mandated emission reductions in other non-aviation sources (i.e., automobiles, power plants, etc.). The EPA recognizes fine PM emissions as a potential health hazard.² As a result, National Ambient Air Quality Standards for PM with an aerodynamic diameter of 2.5 micrometers or less (PM_{2.5}) were implemented on a 24-hr and annual basis. The aerodynamic diameter of jet turbine aircraft PM is extremely small in size, with bimodal peaks in the distribution usually occurring near 30 and 100 nm.³ As such, the PM emissions from commercial jet aircraft may all be considered PM_{2.5}.

The Clean Air Act amendments require emission inventories and dispersion modeling to be performed for aircraft operations in the vicinity of airports to determine aviation's incremental impact on human health, welfare, and air quality.⁴ In addition, strong interest currently exists as to the role aviation emissions play in air quality and climate change issues. These reasons underpin the need to quantify and understand PM emissions from certified commercial aircraft engines.

A certified commercial aircraft engine is defined in this paper as a turbofan jet engine with a rated output equal to or greater than 26.7 kN and included in the International Civil Aviation Organization (ICAO) engine emissions databank.⁵

IMPLICATIONS

This paper supplies practitioners with a methodology to estimate PM emissions from certified commercial aircraft engines within the vicinity of airports worldwide.

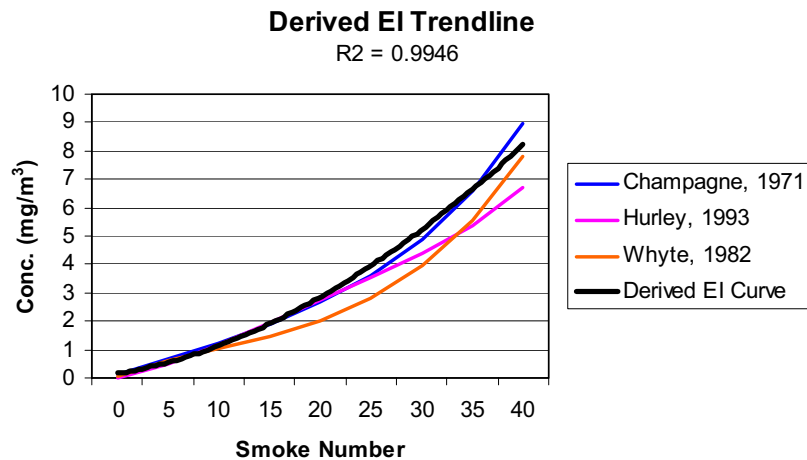


Figure 1. SN correlated with *PM_{nv}* mass for FOA1.0.⁹⁻¹¹

ICAO's Committee for Aviation Environmental Protection (CAEP) sets emission standards for certified commercial aircraft engines, which at the present time only address emissions of carbon monoxide, nitrogen oxides, unburned hydrocarbons, and maximum smoke number. The recognized gap is that a PM emissions standard in terms of mass emissions is not part of the engine certification process. Inclusion of a new PM mass emissions standard would require a standard sampling procedure for the measurement of PM emissions from certified commercial aircraft engines. Establishing a standardized PM sampling procedure is a difficult task complicated by the high temperatures and velocities of the engines' exhaust stream. Nonetheless, the Society for Automotive Engineering International's E-31 committee is charged with developing standardized PM sampling procedures for both nonvolatile and volatile PM emissions. Their work is several years away from completion. In the interim, to ensure compliance with relevant laws, regulations, and standards, there is a need for a robust methodology to estimate PM emissions from certified commercial aircraft engines in the vicinity of airports.

FIRST-ORDER APPROXIMATION METHODOLOGY BACKGROUND

In 2003, a detailed literature review of PM emission methodologies provided the foundation for the development of an initial first-order approximation (FOA) methodology to estimate the nonvolatile PM emissions from certified commercial aircraft engines.⁶ The first FOA, now referred to as FOA1.0, was based on the statistical correlation between smoke number (SN) reported in the ICAO engine emissions databank and the limited data available for nonvolatile PM mass emissions. FOA1.0 only estimated the nonvolatile PM component, often referred to as soot, which is dominated by black carbon but also includes trace metals and other inorganic species. Engine certification standards per ICAO requirements only require the maximum SN to be reported and often this is the only value available in the ICAO engine emissions databank. FOA1.0 used this maximum value, typically representing the highest reported thrust levels. This number was conservatively applied for all modes of operation; namely takeoff, climb out, approach, and taxi/idle. The

full details of FOA1.0 were documented in the literature review and presented at the 2003 Annual Meeting of the Air and Waste Management Association (A&WMA).^{6,7}

The maximum SN measurements required during the certification of new commercial aircraft engines are derived by capturing the PM of the aircraft engine exhaust on a filter and then measuring the reflectance of the filter after deposition.⁸ The extremely small particles inherent in the engine exhaust often penetrate the filter, therefore a portion of the PM mass is not captured during the certification-based SN measurement. How much filter penetration occurs varies by engine. However, various researchers have shown that the mass that is deposited directly correlates with the total mass and the SN. In 2003, the three most recognized studies⁹⁻¹¹ that defined the SN-to-mass correlation were combined as shown in Figure 1, and a conservative approach (i.e., one that tended to overestimate PM mass emissions compared with published data) was derived for use in the FOA1.0 methodology that is also shown in Figure 1. Figures 2 and 3 present the validation efforts of FOA1.0, which were based on independent measured data from the University of Missouri-Rolla and the German Aerospace Center (DLR). The figures illustrate that the methodology appeared to estimate the nonvolatile PM emissions in a meaningful way.

Feedback from the scientific and regulatory peer-review community emphasized that the volatile PM component was important and should be accounted for in the

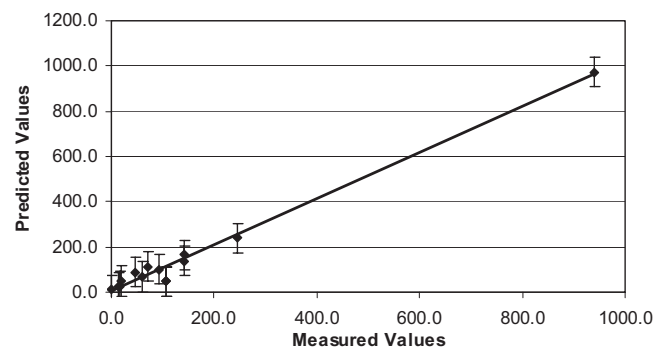


Figure 2. Verification of FOA1.0 comparing measured nonvolatile emission rates to predicted nonvolatile emission rates (mg/sec).

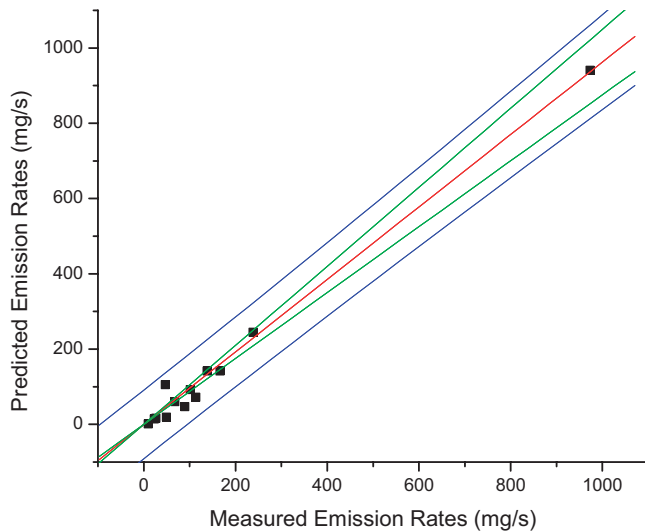


Figure 3. Error limits associated with FOA1.0 comparing measured nonvolatile emission rates to predicted nonvolatile emission rates (trend line in red, 99% confidence limits in green, and 99% prediction limits in blue).

FOA methodology.⁶ These concerns led to further work to include a PM volatile component in the approximation. The PM volatile component is primarily secondary pollutants formed from precursors in the exhaust stream as they mix with the ambient air. In early 2005, work related to the volatile component for the FOA methodology began although the scientific literature related to the volatile component of aircraft PM was extremely sparse. At the time, two measurement studies from the U.S. Navy¹² and EPA,¹³ as well as theoretical studies by Massachusetts Institute of Technology researchers¹⁴ were thought to offer the best insights on the contribution of volatile PM relative to nonvolatile PM by the authors. These studies led to the development of a simple scaling technique based on the relative mass of the volatile PM as compared with the nonvolatile mass fraction. Multiplying the nonvolatile PM estimate by a multiplier was considered to be the best method available at the time, irrespective of the fact that volatile PM is not a direct function of nonvolatile PM. The three referenced sources suggested multipliers of 2, 3, and 2, respectively, of volatile PM to nonvolatile PM. Because of the limited volatile PM data sources, a conservative multiplier of 4 was incorporated into the FOA methodology by the authors of this paper. This scaling technique resulted in FOA2.0 for total PM estimation.¹⁵ EPA approved the use of FOA2.0 for airport inventories in U.S. regulatory studies with a cautionary qualifier regarding the empirical nature of the methodology.¹⁶ The ICAO CAEP also endorsed FOA2.0 as an interim methodology, with a caveat that more work was needed to improve the methodology by decoupling the volatile and nonvolatile components of aircraft PM emissions. In November 2005, a group of international experts, including members from government, industry, and academia, began development of a more robust version of the FOA methodology. They completed their work in October 2006, and in February 2007, ICAO CAEP reviewed and fully accepted the final FOA3.0 methodology for international use.

This paper presents the FOA3.0 methodology, including the equations and related assumptions. FOA3.0 is intended to be used by practitioners to estimate PM emissions from certified commercial aircraft engines within the vicinity of airports worldwide.

FOA3.0 METHODOLOGY

The FOA3.0 methodology contains expressions for each major component of nonvolatile and volatile PM. The volatile PM computation in FOA3.0 has been completely changed from FOA2.0. The development of the volatile component of FOA3.0 began by considering available data regarding the composition of secondary PM and the formation processes. Important components of the volatile PM were identified to be sulfates because of the fuel sulfur content, organics from unburned fuel (incomplete oxidation), and organics from lubrication oil fugitive emissions. Limited available measurement data indicated that nitrate-driven secondary volatile PM was not an important contributor to the total PM.¹⁷ Additionally, the residence time and long-range transport for nitrate-driven secondary PM is too short and too far, respectively, to have an impact on local air quality within the vicinity of an airport. Nitrates were considered to be more of a regional issue. As such, the secondary nitrate PM was not considered within the FOA3.0 equations that represent volatile PM emissions.

Assuming each component contribution to the total PM could be independently quantified, the following general form of the FOA3.0 was used:

$$\begin{aligned} Elvols = & \text{sum of the components (Sulfates + Fuel Organics} \\ & + \text{Lubrication Oil Organics)} \end{aligned} \quad (1)$$

$$Elvols = \text{correlation of the SN-to-Mass Relationship} \quad (2)$$

where *Elvols* is the volatile PM component and *Elnvols* is the nonvolatile PM component. When added together, *Elvols* and *Elnvols* provide the total PM emission index (EI).

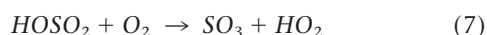
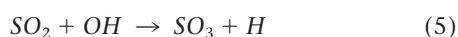
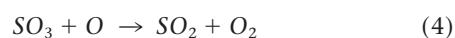
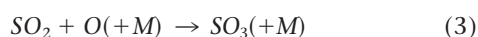
At the engine exit plane, a negligible *Elvols* is expected in particle form because of the high exhaust temperatures (i.e., most precursors are in the gaseous state). However, with increasing distance from the engine exit plane, the exhaust expands, cools, and *Elvols* begin to form. The plume also becomes more dilute as it mixes with the ambient air. The engine exhaust is subjected to varying ambient conditions, which has a direct effect on the formation of volatile PM emissions primarily by condensation. *Elvols* may also form independently upon the surface of the *Elnvols*.

The development of each FOA3.0 calculation methodology is described in the following subsections.

Volatile PM from Fuel Sulfur Content

Jet-A fuel is the prevalent fuel used in certified commercial aircraft engines and contains a small amount of sulfur (limited to 0.3%, but most often less than 0.1% by mass).¹⁸ The fuel is oxidized during the combustion process leading to both gaseous and PM emissions. The sulfur

content of Jet-A fuel varies by geographic region but can be characterized as shown in Table 1.¹⁶ Because the amount of sulfur in the fuel is directly related to the PM emissions, the percent mass of sulfur in the fuel is crucial to the estimation of the sulfur PM emissions. On the basis of Table 1, a conservative value of 0.068% by weight was assumed for FOA3.0. Although well over 90% of the sulfur is oxidized to sulfur dioxide (SO₂), other sulfate compounds are formed, resulting in volatile PM emissions. The sulfur-related PM emissions are comprised of multiple chemical species as the conversion proceeds from elemental sulfur (S^{IV}) to sulfuric acid (H₂SO₄: S^{VI}). Equations 3–8 show the major reactions in the forward direction going from reactants to products.



Not all of the chain reactions go to completion, resulting in intermediate species remaining for periods of time depending on residence time in the atmosphere and atmospheric conditions. In the immediate vicinity of the jet aircraft plume, the time scales are not sufficiently long for complete conversion of the sulfur to H₂SO₄. As such, emitted volatile PM due to fuel sulfur is assumed to be a mixture with a large portion of the products remaining as intermediate chemical species. To approximate the products of this complex reaction process in the immediate vicinity of the aircraft, sulfate with a molecular weight (MW) of 96 was used as a representative value of all sulfur compounds to permit estimation of the volatile PM emissions without considering all possible species.

As previously discussed, the sulfur fractional conversion (ϵ) into the various secondary volatile PM components is small, because most remains as SO₂. Reported ϵ vary from less than 1% to well over 10%, depending on atmospheric residence times and the concentrations of

reacting chemical components in the atmosphere. Short atmospheric residence times exist in the immediate vicinity of commercial aircraft engine operations where concentrations are above what would be expected as background. The published literature^{19–21} supports that for the short atmospheric residence times in the vicinity of aircraft operations, a best estimate of 3.3% was a reasonable assumption for ϵ .²⁰ However, at the time of this writing, a lower default value is being considered based on recent measurements that have not been fully published.

The above assumptions lead to eq 9 to predict the emissions of sulfur-based volatile component of PM (*PMvol*). The EI is given in units of milligrams of volatile sulfur-based PM per kilogram of fuel burned and is directly related to the fuel sulfur content (FSC) and the fractional sulfur conversion.

$$EI_{\text{vol-FSC}} \left[\frac{\text{mg}}{\text{kg fuel}} \right] = 1 \times 10^6 \left(\frac{\text{FSC}(\epsilon) \text{MW}_{\text{out}}}{\text{MW}_s} \right) \quad (9)$$

where

$$EI_{\text{vol-FSC}} = EI \text{ for FSC}$$

$$\text{FSC} = \text{the FSC (mass ratio with default 0.00068)}$$

$$\epsilon = \text{the S}^{\text{IV}} \text{ to S}^{\text{VI}} \text{ fractional conversion (default 0.033)}$$

$$\text{MW}_{\text{out}} = 96 \text{ (sulfate in exhaust)}$$

$$\text{MW}_s = 32 \text{ (S}^{\text{IV}} \text{ in fuel).}$$

Equation 9 may be simplified to:

$$EI_{\text{vol-FSC}} [\text{mg/kg fuel}] = 3 \times 10^6 (\text{FSC})(\epsilon) \quad (9a)$$

PMvol Organic Contribution

The organics that contribute to *PMvol* primarily arise from chemical species with a vapor pressure sufficiently low to allow condensation in the atmosphere. These chemical species, present in small amounts, are primarily products of incomplete combustion. These *PMvol* chemical species may include both partially oxidized fuel fragments and species formed in the combustion chamber because of pyrolysis. As was the case with FSC, residence time and atmospheric conditions are important considerations for estimating the *PMvol* contribution.

Measurement data from the recent Aircraft Particle Emissions Experiment (APEX1)^{13,17} campaign were more representative of certified commercial aircraft engines in today's fleet than previously available data, such as that reported by Spicer.²³ APEX1 also included measurements from a probe 30 m behind the engine, thereby providing data of the jet plume after being subjected to atmospheric cooling.

Although only one engine was measured (CFM56-2-C1), the APEX1 data based on two test periods does provide valuable insight into organic *PMvol* emissions. Figure 4 includes a graphical representation of the APEX1 data and includes the four characteristic ICAO certification thrust settings: idle (7%), approach (30%), climb out

Table 1. Representative FSC of various aviation fuels.²²

Fuel	Total Sulfur Weight Content (%)
Jet A	0.068
Jet A-1	0.046
JP-8 (U.S.)	0.049
JP-5	0.047
JP-7	0
JP-TS	0.026
JP-4	0.046
Avgas grade 100LL	0.005

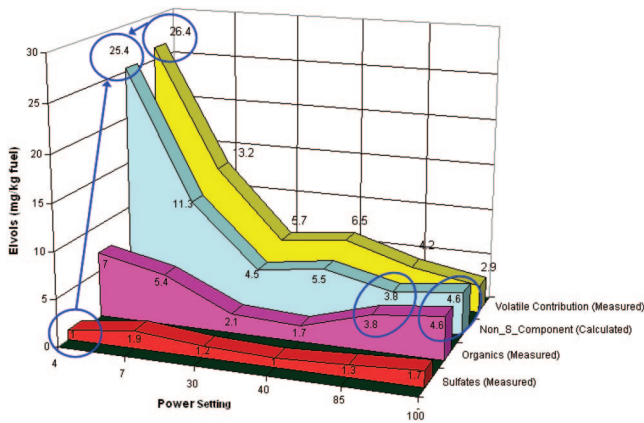


Figure 4. Trends from APEX 1 for CFM56-2-C1 engine¹⁷ (40% power setting was reported but is not an ICAO-defined mode and not used in FOA3.0).

(85%), and takeoff (100%).⁵ Of note is that 40% rated thrust was reported and included in the figure for completeness but is not used in FOA3.0 because 40% rated thrust is not associated with other certification data in the ICAO engine emissions databank.

The volatile contribution curve shown in Figure 4 represents the mass emitted per kilogram of fuel burned for the total *PMvol*. The volatile contribution was obtained by comparing results with and without an inline 300 °C thermal denuder before being measured using a scanning mobility particle sizer.¹⁷ This resulted in measurements with and without condensation, which permitted an evaluation of *PMvol* emissions that could condense in the atmosphere.

The values for the sulfates curve (see Figure 4) were subtracted from the volatile contribution to avoid double counting sulfate-driven *EIVols*. By subtracting the sulfate-driven *EIVols*, non-sulfur *PMvol* components were defined. However, this method is questionable at higher power settings of 85 and 100% because the defined organic values were less than the measured organic fraction by other researchers using an aerosol mass spectrometer (AMS) during the same test (see organics curve shown in Figure 4). Because there was no way to determine which was the more accurate value for these two higher power settings, the *PMvol* organics component for the two high-power settings were set to the greater and more conservative values from the AMS-measured organics. This led to the results for the CFM56-2-C1 engine as shown in Table 2 and the *Non_S_Component* curve in Figure 4. The values in the table and figure represent the volatile contribution without sulfur components being included.

Table 2. Derivation of organic volatile fraction *Non_S_Component* for FOA3.0.

Power Setting (% power)	Mode	Sulfates (mg/kg fuel)	Organics (mg/kg fuel)	Volatile Contribution (mg/kg fuel)	<i>Non_S_Component</i> (mg/kg fuel)
7	Idle	1.9	5.4	13.2	11.3
30	Approach	1.2	2.1	5.7	4.5
85	Climb out	1.3	3.8	4.2	3.8
100	Takeoff	1.7	4.6	2.9	4.6

The limited availability of data for organic-driven *EIVols* required two important assumptions to be made. First, pollutant trends from the recent research of APEX1, as shown in Figure 4, are assumed to be consistent for all certified commercial aircraft engines in the ICAO engine emissions databank. Second, fuel organic PM emissions are assumed to be proportional to total hydrocarbon (HC) EIs measured during engine certification (as total HC emissions increase so do the precursors of organic PM components in the exhaust plume). These two assumptions enabled estimation of fuel organic-driven *PMvol* emissions for other engines in the ICAO engine emissions databank.

Two possible methods were considered for the FOA3.0 methodology to predict the mass emissions of organics: one being mode-specific for each of the ICAO power settings as previously defined, and the other based on a complete landing/takeoff (LTO) cycle at an airport.⁵

Method 1—Mode-Specific. This estimation methodology, based on the two assumptions above, uses the ratio of the HC modal EIs for any selected engine in the ICAO engine emissions databank to those for the CFM56-2-C5, which was the closest match to the engine measured in APEX1. This ratio represents the relative rate factor of HC for any engine selected as compared with the CFM56-2-C5 engine. This rate factor is multiplied by the volatile fraction derived for the APEX1 test engine (*Non_S_Component*). This allows estimation of the volatile fraction for the specified engine by mode as shown in eq 10.

$$EI_{\text{vol-FuelOrganics}} = \frac{\text{Non_S_Component}}{EI_{\text{HC(CFM56)}}} (EI_{\text{HC(Engine)}}) \quad (10)$$

where

$$EI_{\text{vol-FuelOrganics}} = \text{volatile PM emissions of fuel organics (mg/kg fuel)}$$

$EI_{\text{vol-FuelOrganics}}$ is the *PMvol* emissions of fuel organics (mg/kg fuel), *Non_S_Component* is a value derived from CFM56-2-C1 trends by subtracting sulfate components from measured volatile emissions as described in text (mg/kg fuel), $EI_{\text{HC(CFM56)}}$ is the mode-specific HC EI for CFM56-2-C5 engine (g/kg fuel), and $EI_{\text{HC(Engine)}}$ is the mode-specific HC EI for the engine of concern (g/kg fuel).

Of note is that eq 10 must be repeated for each of the four defined modes. Because *Non_S_Component* and $EI_{HC(CFM56)}$ are constants for each mode, eq 10 can be reduced to eq 10a.

$$EI_{vol-FuelOrganics} = \delta[EI_{HC(Engine)}] \quad (10a)$$

where

$$\delta = \left(\frac{Non_S_Component}{EI_{HC(CFM56-2-C5)}} \right) \text{ by mode (mg/g)}$$

Table 3 shows the mode-specific constant values for δ , the ratio of *Non_S_Component* and the $EI_{HC(CFM56)}$.

The $PM_{vol-FuelOrganics}$ value for the entire LTO cycle is largely influenced by the amount of time an engine is operated in idle mode, because the HC EI value is largest in idle mode and the idle time is far longer than other modal times within the LTO cycle. To get an understanding of what portion of total LTO HC emissions contributes to *PMvol* formation, the certification times in mode were applied to all engines in the ICAO engine emissions databank, and eq 10 was then applied. These results indicated that *PMvol* contribution from fuel organics is on average 1.3% of the total LTO HC emissions.

Method 2—LTO-Based. Because data were so sparse, a second simplified method was considered based on applying results across the entire LTO cycle. This method is based on the ratio of the total non-sulfur volatile component across the entire LTO cycle versus the total LTO HC emissions for the CFM56-2-C1 engine. This yields a multiplier of 0.85% times the total HC emissions for the entire LTO cycle for an engine of concern. Equation 11 provides the formula to calculate the *PMvol* created by fuel organic emissions ($PM_{vol-FuelOrganics}$).

$$PM_{vol-FuelOrganics} \text{ (grams)} = (0.0085) \text{ (Total LTO HC emissions for Engine of Concern)} \quad (11)$$

There is only a small difference between the results when either eq 10 or 11 is used (1.3 vs. 0.85% of total LTO HC emissions). However, eq 10 does permit modal analysis whereas eq 11 is for the entire LTO cycle. Because the results may be needed in different formats according to the purpose of use, the final decision is left to the user. In the United States, the Federal Aviation Administration (FAA) prefers the mode-specific approach because time spent in the idle mode varies considerably at airports

Table 3. Values of the HC EI from the ICAO databank and derived mode-specific values of δ for FOA3.0.

Mode	ICAO HC EI (g/kg fuel)	δ Numeric Value
Takeoff	0.04	115
Climb out	0.05	76
Approach	0.08	56.25
Idle	1.83	6.17

whereas the other modes are more consistent. In this way, the idle emissions are estimated in a more flexible fashion.

PMvol from Lubrication Oil

PMvol emissions are likely affected by lubrication oil emissions. Although the physical and chemical makeup of lubrication oil is well known, there are many variables that require further investigation to determine the magnitude of influence on *PMvol* emissions. This includes how to identify different configurations of venting lubrication oil emissions not only by engine type but by airframe as well. The detail to determine each venting location for each engine/airframe combination could be obtained, but the lack of measurement data prevents researchers from developing a direct quantification methodology at this time. Accordingly, lubrication oil has been included in eq 1 shown earlier and is still an area of concern, but is not calculated by FOA3.0.

However, the authors assumed that the influence of lubrication oil on the formation of *PMvol* while in the exhaust plume is included in the fuel organic EI described above in eqs 10 and 11 because the volatile contribution was derived for the CFM56-2-C1 engine. This engine, on the airframe tested, includes a lubrication oil vent in the exhaust plume. This results in the lubrication oil component being measured as part of the volatile fraction and included in the $EI_{vol-FuelOrganics}$ term, although in aggregate form.

Nonvolatile PM (Soot) from Correlation with SN

As described earlier, multiple researchers have shown that SN correlates well with nonvolatile PM mass emissions.^{6,9-11} As such, and because of a complete dataset, the nonvolatile PM methodology for FOA3.0 is again based on available PM mass measurement data compared with the reported SNs from the ICAO engine emissions databank. For FOA3.0, the database of PM mass emissions compared with the SN that was used in the statistical analysis was expanded as described in the following text. Additionally, during the statistical analysis, a better correlation was achieved if the data were divided into two groupings, below and above a SN of 30. Most modern engines in the fleet have a SN less than or equal to 30, but some older engines with a SN greater than 30 remain in the fleet.⁵

For estimating nonvolatile PM emissions for SNs less than or equal to 30, the authors included more recent laboratory experimental data supplied by the QinetiQ Laboratories of the United Kingdom²⁴ to establish a relationship between SN and nonvolatile PM mass. As such, the database was expanded from that used in FOA1.0 and 2. These data appeared to be reasonable when compared with independent in situ measurement data of nonvolatile PM mass emissions reported by Petzold et al.³ and Whitefield et al.²⁵ The statistical analysis of these data, based on a least-square fit of mass per unit volume of exhaust to SN, yielded a concentration index (CI). The CI is the mass per standard volume of exhaust in which standard conditions are 0 °C and 1 atm of pressure. The derived general equation for the best estimate of fit was (best data correlation SN \leq 30):

$$CI = 0.0694(SN)^{1.24} \quad (12)$$

where

CI = concentration index (mg/M³)
SN = smoke number

Because confidence limits are difficult to predict because of the small amount of available data, an upper bound to the CI was considered. The largest uncertainty due to this correlation is the error in the measurement of the SN. The maximum error in SN measurement is estimated to be ± 3 in number^{26,27} and when used in the FOA methodology produces a maximum bound. The error in mass measurements is very small in comparison, and although reviewed it was not included because of the very small change. Using this assumption, the authors generated a new database using eq 12 with all SNs increased by three and then developed corresponding best-fit equations. This led to eq 13, which represents an upper bound to the CI.

Upper bound for SN ≤ 30

$$CI = 0.0012(SN)^2 + 0.1312(SN) + 0.2255 \quad (13)$$

The decision to use eq 12 or 13 was left to the user depending on if a best estimate or an analysis of the upper bound to account for uncertainty was desired. The lower bounds (if SN error was -3) were also considered but dismissed because this method could lead to gross underprediction and therefore should not be used to estimate nonvolatile PM (*PM_{nv}*) emissions.

For SNs greater than 30, a different dataset was used. In this case, data from detailed smoke-generator testing supplied by Hurley²⁴ as well as data by Whitefield et al.²⁵ were used in the analysis. The resulting correlations were as follows and should be applied for those few engines with SN greater than 30 still in the fleet.

Best estimate:

$$CI = 0.0297(SN)^2 - 1.802(SN) + 31.94 \quad (14)$$

Upper bound:

$$CI = 0.0297(SN)^2 - 1.6238(SN) + 26.801 \quad (15)$$

Using the CI equations, the *PM_{nv}* CI can be estimated for any engine using the SNs from the ICAO engine emissions databank. The ICAO databank includes SNs for certified commercial aircraft engines, but regulations only require the maximum to be reported, which was a problem when using FOA1.0 and 2. Therefore, SN data for all

Table 4. Representative AFRs by power setting.

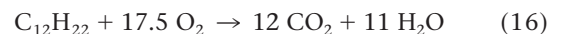
Power Setting	AFR
7% (idle)	106
30% (approach)	83
85% (climb out)	51
100% (takeoff)	45

Table 5. Representative engine volumetric flow rates by mode.

Mode	Predicted Volumetric Core Flow Rate (m ³ /kg fuel)
Idle	83.1
Approach	65.3
Climb out	40.5
Takeoff	35.8

four defined power settings (idle, approach, climb out, takeoff) are not reported for all engines during certification. Obtaining SN by power settings is desirable to use the approach presented herein. To fill in the missing SN information for all modes and all engines, researchers developed a procedure on the basis of categories of certified commercial aircraft engine types and consideration of the combustor type.²⁸ The combustor type used is an important parameter in *PM_{nv}* production, with a large difference between single and dual annular combustors. Using this approach, the trends of each group in the ICAO engine emissions databank were reviewed and the SN values populated for all four power settings and most engines in the databank. This permitted estimation of the mass EIs by engine power setting or mode.

Final calculation of the nonvolatile estimate of PM EI requires one additional step, the calculation of the exhaust volumetric flow rate. This can be calculated based on the mass air-to-fuel ratio (AFR) and the molar quantities of the oxidation chemical reaction of the fuel combustion. The AFR and the exhaust flow vary from engine to engine and different engine power settings (idle/taxi, approach, climb out, takeoff). Because the exact AFR is proprietary, an average AFR per power setting is assumed for all certified commercial aircraft engines. These average AFRs were reviewed by commercial jet engine manufacturers and considered reasonable. The values for each mode are shown in Table 4.²⁹ Using these values, an equation can be defined to predict core engine flow. This is done by first assuming Jet-A fuel has the chemical makeup of C₁₂H₂₂, which leads to the stoichiometric equation:



Then, using densities at standard temperature and pressure (allowing for the change in water vapor at lower temperatures), on a 1 kg of fuel basis the reduced equation becomes:

$$Q_{core} = 0.776(AFR) + 0.877 \quad (17)$$

where

Q_{core} = Core exhaust volumetric flow rate per kg of fuel burn (m³/kg fuel)

AFR = modal mass air-to-fuel ratio

Table 5 lists the volumetric core engine flow per kilogram of fuel burn predicted for each mode.

In some cases, the SN may be measured under mixed flow conditions, in which the core engine flow may be mixed with bypass flow. The user must check the column

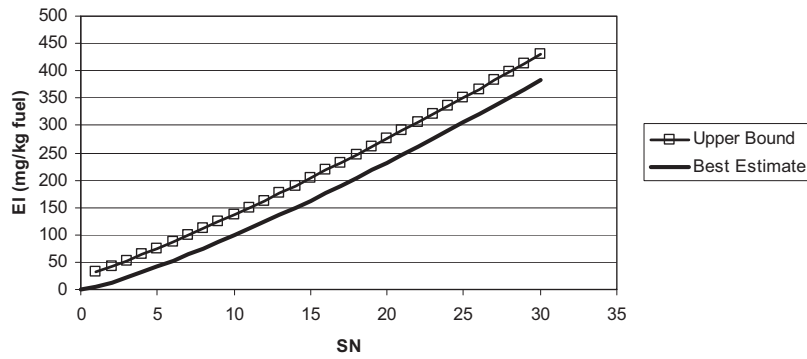


Figure 5. Plot of EI for the idle mode for SN ≤ 30.

in the ICAO databank with the heading “Eng Type.” A listing of “TF” (turbofan) means that only core flow should be used in the estimate. However, a listing of “MTF” (internally mixed turbofan) indicates that bypass flow was also included during the measurement of the SN and the flow must be adjusted. To adjust for this condition, eq 17 is corrected by including the bypass ratio (β) in the calculations. β is also included for each engine in the ICAO engine emissions databank (column heading “B/P Ratio”) and should be included in calculations, as shown by eq 18.

$$Q_{\text{mixed}} = [0.776(\text{AFR})(1 + \beta)] + 0.877 \quad (18)$$

Once flow and the CI have been calculated, the EI for PM_{nv} may be calculated from the common continuity equation approach.

$$EI_{\text{nv}} = (Q)(CI) \quad (19)$$

where

- EI_{nv} = non-volatile PM Emission Index (mg/kg fuel)
- Q = either Q_{core} or Q_{mixed} as appropriate (std. m^3/kg fuel)
- CI = emission concentration index (mg/std. m^3)

Using eq 19 with the appropriate CI (eq 12–15, as appropriate) and Q (eq 17 or 18; with or without applying β , as appropriate) results in a solution for eq 2 for EI_{nv} .

Figure 5 shows a sample plot of the EIs at idle from

this new methodology for SNs less than 30, whereas Figure 6 shows a sample plot for the idle mode for SNs greater than 30. In the case of estimates for SN greater than 30, a small adjustment was made to the γ -intercept of each mode to coincide with the more used values derived for SNs less than 30 so that a smooth transition occurs between the two equations.

Figures 5 and 6 show a best estimate and an upper bound. The limits were derived by assuming that an error of ± 3 in SN measurements could occur as described above.

FOA3.0 Implementation

In summary, the component calculation EI approach for FOA3.0 is:

$$\begin{aligned} EI_{\text{nv}} = & (\text{Fuel Sulfur Component}) [\text{Equation 9 or 9a}] \\ & + (\text{Fuel Organic Component}) \\ & [\text{Equation 10, 10a, or 11}] \quad (20) \\ & + (\text{Lubrication Oil Component}) \\ & [\text{no recommended methodology at this time}] \end{aligned}$$

$$\begin{aligned} EI_{\text{nv}} = & (\text{SN vs. Mass Relationship}) \\ & [\text{Equation 12 or 13 for SN} \\ & \leq 30 \text{ or Equation 14 or 15 for SN} \quad (21) \\ & > 30] \text{ multiplied by (Exhaust Flow)} \\ & [\text{Equation 17 or 18}] \end{aligned}$$

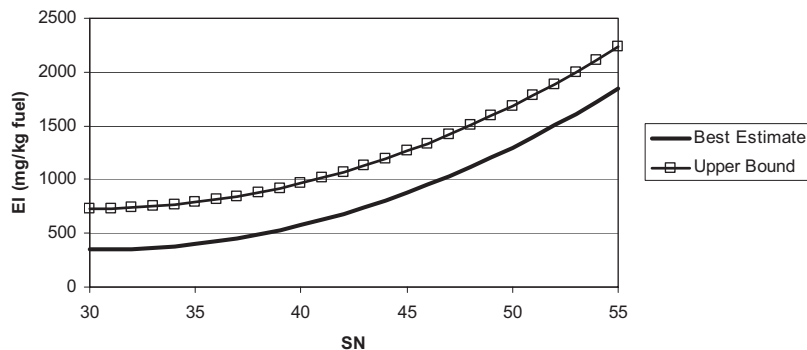


Figure 6. Plot of EI for the idle mode for SN > 30.

$$\text{Total PM} = \text{EI}_{\text{vol}} + \text{EI}_{\text{nvols}} \quad (22)$$

All EI calculations should be multiplied by fuel flow for the respective mode and summed to get total PM mass emissions for a specified engine. The number of engines per aircraft, fleet aircraft types in use, and relative times in each mode must be considered to compute the emission inventory. In addition, spatial and temporal variations are needed to conduct dispersion analysis.

It should be noted that variables have been defined by FAA for use in the United States. Users should contact the local office of FAA to ensure the variables used are correct.

CONCLUSIONS

FOA3.0 represents a significant advancement in methodology over previous versions to estimate PM emissions from certified commercial aircraft engines in the vicinity of airports. The methodology uses the latest scientific information available and unlike previous methods is restructured in a flexible manner to accommodate new scientific advancements as they become available. The restructuring permitted *PM_{nvols}*, sulfur-related volatile compounds, and fuel organics to be estimated as separate, independent processes. The total PM is then the sum of the three components. This permits flexibility in estimation and additional uses of the data (i.e., impacts in changes of FSC) that were not possible before. The component flexibility also permits the model development to continue for each PM component independently as the scientific information knowledge base increases.

FOA3.0 provides a greater confidence in the estimation of PM from certified commercial aircraft at airports. These estimations provide a means to analyze the emissions and the effects in changing operations or aircraft types. Teamed with dispersion models, FOA3.0 can also permit evaluations compared with standards or regulations that are health-based.

FOA3.0 results are intended strictly for airport operations inventory purposes at this time, but future work has been identified to continue to increase the accuracy, applicability, and confidence in the FOA methodology. Once an accepted, repeatable method for direct measurement of PM emissions is established and today's fleet is sufficiently represented, the FOA methodology will eventually become obsolete.

NOMENCLATURE

<i>AFR</i>	= modal mass air-to-fuel ratio
<i>CI</i>	= concentration index (mg/M ³)
<i>EI</i>	= emission index (mg/kg fuel)
<i>EI_{HC(CFM56)}</i>	= mode-specific HC EI for CFM56-2-C5 engine (g/kg fuel)
<i>EI_{HC(Engine)}</i>	= mode-specific HC EI for the engine of concern (g/kg fuel)
<i>EI_{nvols}</i>	= total nonvolatile PM EI (mg/kg fuel)
<i>EI_{vol}</i>	= total volatile PM EI (sum of all components) (mg/kg fuel)
<i>EI_{vol-FSC}</i>	= volatile EI attributable to FSC (mg/kg fuel)
<i>EI_{vol-FuelOrganics}</i>	= volatile PM emissions of fuel organics (mg/kg fuel)

FSC = fuel sulfur content (mass ratio with default 0.00068)

MW_{out} = 96 (sulfate in exhaust)

MW_S = 32 (sulfur)

Non_S_Component = a value derived from CFM56-2-C1 trends (mg/kg fuel)

PM = particulate matter

PM_{vol} = volatile PM component

PM_{nvols} = nonvolatile PM component

Q = core or mixed flow depending on engine test parameters during SN measurements (m³/kg fuel)

Q_{core} = core exhaust volumetric flow rate (m³/kg fuel)

Q_{mixed} = exhaust volumetric flow rate including core and bypass flow (m³/kg fuel)

SN = smoke number

ϵ = S^{IV} to S^{VI} fractional conversion (default 0.033)

$\delta = \left(\frac{\text{Non_S_Component}}{\text{EI}_{\text{HC(CFM56-2-C5)}}} \right)$ by mode or overall average (mg/g)

β = bypass ratio

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